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THE CHARACTERISTICS, DESIGN AND APPLICATIONS OF SWITCHED RELUCTANCE MOTORS AND DRIVES

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1 INTRODUCTION

This tutorial is intended to give a coherent explanation of the technology of the Switched Reluctance (SR) Drive for engineers who are involved with electrical drives, whether as researchers, designers or users. This type of drive is a relative newcomer to the drives market, but it is already widely seen as an option alongside the established types using dc, synchronous, asynchronous and brushless permanent-magnet motors. The drive is being applied in very diverse areas ranging through domestic, industrial, traction, automotive, aerospace, mining....

The subject matter of the tutorial is divided into four sections:

i) Section 2 gives firstly a general background to the range of drive characteristics commonly encountered in practice, with their defining parameters. This background is important if the characteristics and properties of the SR drive are to be appreciated. Illustrations of typical applications are included.

   Secondly, Section 2 introduces the basic structure, components and principles of operation of the SR drive. The intrinsic attractive qualities of the drive are outlined.

   Finally in Section 2, elementary analysis is used to derive the basic natural characteristics and control principles which lie at the heart of the successful exploitation of the SR machine in a flexible controlled drive.

ii) Section 3 is concerned with the SR motor. It develops the elementary theory of Section 2 to include the nonlinear magnetic behaviour of the machine. A correct understanding of the nonlinear relationships between flux, current and angle of rotation is essential for the successful designer of an SR drive, and computer-based modelling is necessary for performance prediction. A dicussion of these topics is followed by a consideration of the fundamental design options for the motor designer and how the choices relate to the specification. Mechanical and thermal features are discussed next and these are followed by the questions of noise and torque ripple. Finally, a number of practical motors are described to illustrate the above design features.

iii) Section 4 deals with the operation and design of the power and control electronics which are an essential component of the drive. Although the machine and the electronics are treated in separate Sections of this tutorial, it is important to realise that the SR drive is designed as a whole in order best to meet a given specification. The basic design options fundamental to the design of the machine, such as phase and pole number, equally influence the choice of power electronic configuration, and together they have major cost and performance implications; at a more subtle level, the machine design can be influenced by the selection of the most economic power switching devices.This Section deals first with the operation and design of the power converter and then with the control strategy and its practical implications.

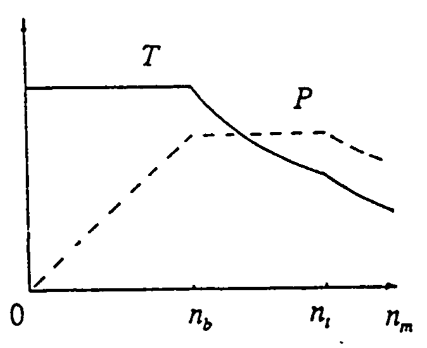
iv) The tutorial concludes with Section 5, which is a review of the material covered in the earlier Sections, and a discussion of a number of practical drives drawn from diverse applications, and, finally, a consideration of the principal markets and the likely impact of SR technology.

2 DRIVE CHARACTERISTICS AND THE BASIC SR DRIVE

2.1 Drive Properties and Characteristics

Figures 1a and 1b show the most commonly encountered torque/speed and power/speed characteristics for a controlled drive. (Note that 1a and 1b are the same, except that the axes have been reversed. Both conventions for drawing the characteristics are frequently used.)

How should these characteristics be interpreted? The curves show that the drive is capable of developing the given constant torque at all speeds up to some speed (n_b), usually called 'base speed'. The mechanical output power is the product of torque and speed and therefore rises linearly with speed at a constant torque. Sometimes the base speed is also the maximum speed of the drive, but as the curves show, the drive may offer a higher range of speed in which the power is constant between the base speed and the 'top speed', n_t. This may not be the maximum speed of the drive (see below).



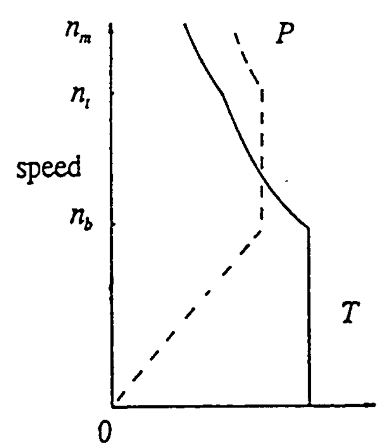


Figure 1 (a) (b)

It is most important for the interpretation of these characteristics to be clear on two further points:

i) The definition used above for defining the curves as those that the drive 'is capable of developing' is imprecise. It may be that the curve represents the maximum possible output at any speed. On the other hand it may represent the maximum continuous output, with higher short-term overloads being possible. Or the curve may be defined by a combination of these reasons, e.g. it may be defined by the thermal rating at low speeds, but by the maximum output line at high speeds.

ii) The curves generally define a **region** of operation in the torque/speed plane. The electronic controller allows the drive to run at all lower torques in the given speed range. However the region at and close to zero speed is sometimes subject to special constraints and the potential user should be careful to select a drive which matches the needs of his application in this area.

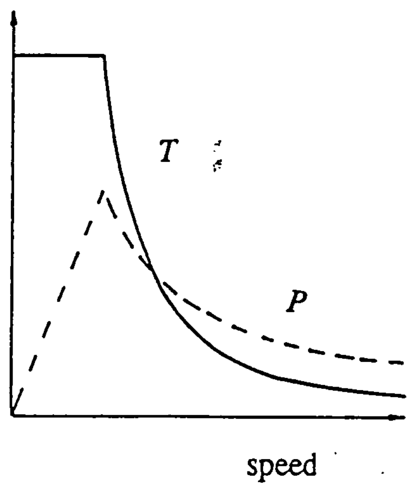


Figure 2

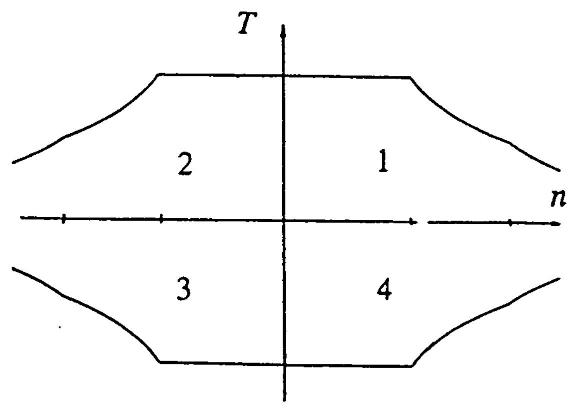


Figure 3

Figure 2 shows another characteristic often encountered; this is the so-called 'series' type. Here the basic torque/speed characteristic approximates to the torque falling inversely as the square of the speed and the power, therefore, as the inverse of the speed. The maximum torque is shown in the Figure to be limited to a constant value, because this is usually constrained by the rating of the electronic controller. In some drives this series characteristic is offered at high speeds, above the region of constant power up to the 'maximum speed', n_m, as shown in Figure 1.

Electrical machines can operate as motors or generators, depending on whether mechanical power is drawn from or supplied to the shaft. The electronic controller can be designed to control the machine with both directions of power flow: Figure 3 shows the most flexible form of characteristic. This allows the machine to operate as a motor or generator in either direction of rotation; motoring in quadrants 1 and 3, and generating in quadrants 2 and 4. (The power flow is negative, corresponding to generation, when either the torque or the

speed are negative, but not both.) Not all 4-quadrant drives allow a smooth, controlled torque and/or speed reversal.

A further subdivision of those drives offering regenerative operation is whether the power converted from mechanical to electrical form can be returned to the electrical supply (and therefore recovered) or whether it is dissipated ('dumped') in a resistor (so-called 'regenerative braking'). This resistor and its controller may be offered as an optional addition to the basic drive, when the enhanced performance which it offers is required. Sometimes, when it is relatively small, the regenerated energy is absorbed as heat in the machine and the electronics.

Finally in this list of drive characteristics, it is important to note that drives differ in the kind of speed control (open loop or closed loop) and in the range of control offered with a given degree of speed holding (e.g. 10:1, 100:1) and in their dynamic performance, with servo systems offering the highest rates of change of torque and speed.

2.2 SR drive principles

In construction, the SR motor is the simplest of all electrical machines, with no electrical conductors or permanent magnets on the rotating part and only simple, electronically-switched coils , carrying unidirectional currents, on the stator. This attractive combination of a robust, simple motor, coupled with the rapidly evolving capabilities and falling costs of power-electronic switches and control electronics has been the inspiration for its development.

Historically, the reluctance motor has been thought to be incapable of competing effectively with other types. However, deepening understanding of motor design and the application of controlled electronic switching have resulted in a drive system capable of very high levels of performance over a very wide range of sizes, powers and speeds.

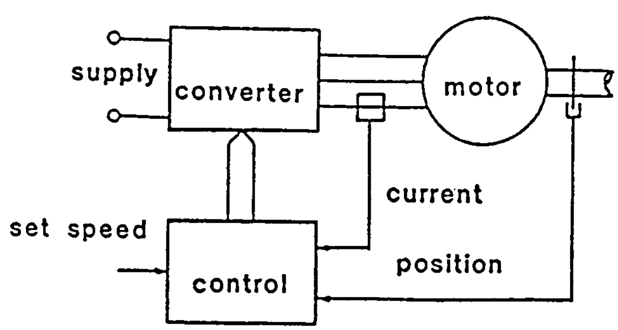


Figure 4

Figure 4 shows the principal components of an SR drive system. The input power supply can be either a battery or rectified and filtered mains. (In this respect it is the same as a voltage-fed inverter for an induction motor drive.) The dc voltage is switched across the phase windings of the motor by the power converter under the control of the electronic control unit. It is fundamental to the operation of the drive that the switching is correctly synchronised to

the angle of rotation of the rotor, and it is usual to have some form of simple rotor position encoder on the motor shaft to supply signals to the control electronics. This same encoder can be used to generate a speed feedback signal in the control electronics and Figure 4 shows this being utilised to give closed-loop speed control.

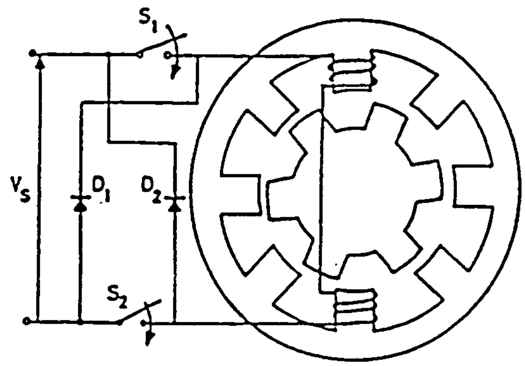


Figure 5

Figure 5 shows the elements of a 4-phase SR motor. (The choice of phase and pole number will be discussed in Section 3.) It has 8 salient poles on the stator and 6 on the rotor. Both the stator and the rotor are laminated. Each stator pole carries a simple exciting coil, and opposite coils are connected to form the N and S pole pairs of one 'phase'. The rotor has **no electrical circuits or permanent magnets**. Only one phase winding is shown, excited from the dc supply through 2 switches (in practice some form of electronic switch), with 2 diodes to allow energy to return to the supply. (Other switching configurations are possible and these will be discussed in Section 4.)

Torque is developed by the tendency for the magnetic circuit to adopt a configuration of minimum reluctance, i.e. for a pair of rotor poles to be pulled into alignment with an excited pair of stator poles, maximising the inductance of the exciting coils. Continuous rotation (in either direction) is assured by switching the phases in the appropriate sequence, so that torque is developed continuously in the appropriate direction. In simple terms, the larger the current supplied to the coils, the greater the torque.

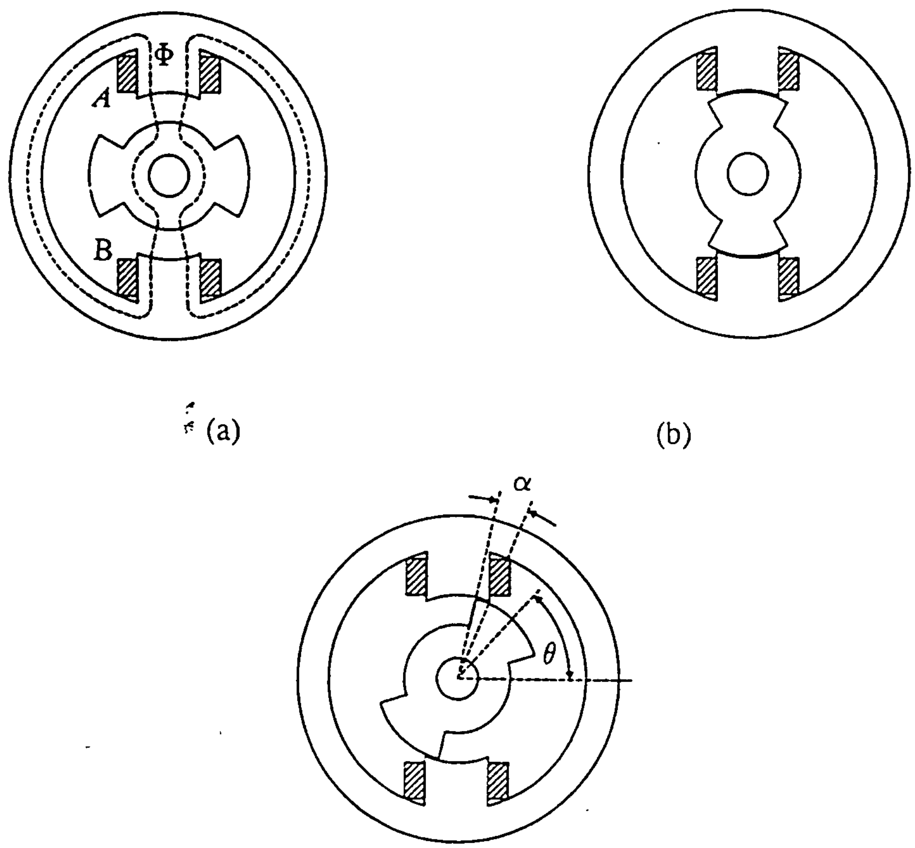
Note that the torque is independent of the direction of current flow, so that **unidirectional** currents can be used, regardless of the quadrant in which it is operating. This permits a simplification of the electronic switching circuits compared with those required for most other forms of motor. It should also be noted that stator coils are always connected in series with the power switches, so that there is no low-impedance 'shoot-through' fault path, such as occurs in inverters for conventional drives.

Summarising, the SR motor and controller are extremely robust. The motor has simple coils, with small endwindings and no overlapping of phase windings; the rotor has no coils or magnets. The power converter, which uses electronic power switches, has to supply only

unidirectional currents and the maximum rate of rise of switch current is limited by the stator coils, thus avoiding the possibility of 'shoot-through' faults.

2.3 Basic Analysis

2.3.1 Torque production and power flow



(a) (b) (c)

Figure 6

Figure 6 shows the simplest configuration of SR motor. This has only one phase, with a coil on each of two stator poles. The coils (A and B) are connected in series or parallel in the appropriate sense to assist each other in producing a '2-pole field' distribution. The rotor has two salient poles.

In Figure 6a, the rotor is shown in the misaligned position. The effective airgap presented to the magnetic circuit is maximum. The flux, Φ, linking the coils is therefore a minimum for a given current, and therefore the inductance (the flux linkage per ampere) is also a minimum.

In contrast, in Figure 6b the rotor is in the fully aligned position. The effective airgap has its minimum value and the inductance is maximum.

Figure 6c shows an intermediate position, in which the poles are overlapping by an angle α. Clearly, the inductance will have some value between maximum and minimum.

For a basic appreciation of the operation of the machine it is sensible to simplify the picture of the magnetic field in the airgap by neglecting the fringing field at the tips of the poles (i.e. to assume that all the flux crosses the airgap radially) and therefore to assume that, for a given current, the flux remains constant at its value in the minimum inductance position until the poles begin to overlap. The flux then increases linearly with the overlap angle, α of Figure 6c, as the area of the stator and rotor pole faces confronting each other increases linearly with α. The resulting variation in winding inductance is shown in Figure 7a. The physical significance of the regions of variation of inductance need to be considered:

> θ_0 - θ_1 : at θ_0 the 'leading' edges of rotor poles meet the edges of stator poles and the inductance starts a linear increase with rotation, continuing until the poles are fully overlapped at θ_1, when the inductance reaches its maximum value L_{max}.
>
> θ_1 - θ_2 : from θ_1 to θ_2 the inductance remains constant at L_{max} through the region of full overlap. This region, generally known as the 'dead zone', exists when the stator and rotor pole arcs are unequal.
>
> θ_2 - θ_3 : from θ_2 to θ_3 the inductance decreases linearly to the minimum value, L_{min}.
>
> θ_3 - θ_4 : from θ_3 to θ_4 the stator and rotor poles are not overlapped and the inductance remains constant at L_{min}.

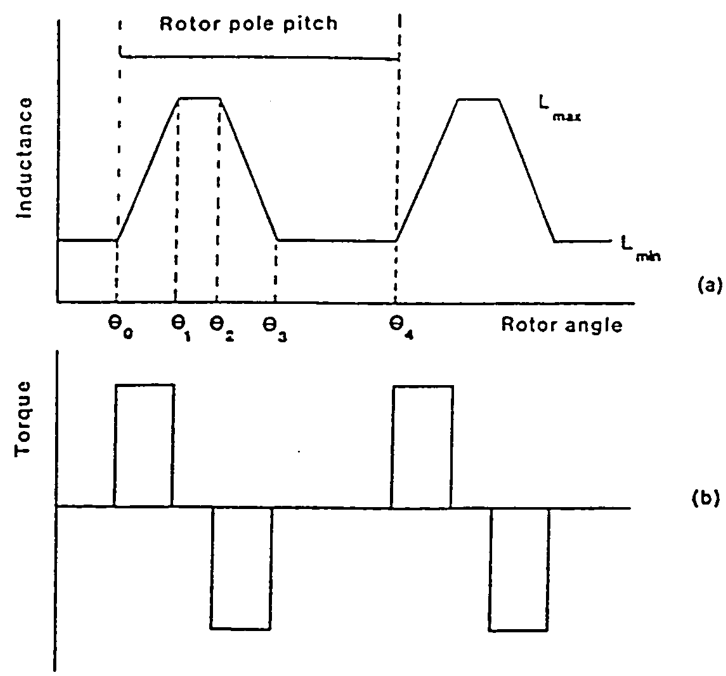


Figure 7

Having defined the variation of inductance with angle of rotation, it is a simple matter to derive an expression for the torque as a funtion of the angle and of the exciting current.

The general equation governing the flow of stator current, i, may be written

$$v = Ri + \frac{d\psi}{dt} \tag{1}$$

where v is the voltage (of appropriate polarity) applied across the winding, R is the winding resistance and ψ is the flux linking the coil.

The flux linkage is related to the inductance by the equation

$$\psi = Li \tag{2}$$

and so Equation 1 can be rewritten

$$v = Ri + \frac{d}{dt}(Li) \tag{3}$$

in which both L *and* i are, in general, functions of time.

Equation 3 can therefore be written

$$\begin{aligned} v &= Ri + L\frac{di}{dt} + i\frac{dL}{dt} \\ &= Ri + L\frac{di}{dt} + i\frac{dL}{d\theta}.\frac{d\theta}{dt} \\ &= Ri + L\frac{di}{dt} + i\frac{dL}{d\theta}.\omega \end{aligned} \tag{4}$$

where ω is the rotational speed in radians per second. The third term is sometimes called the 'motional emf'.

The electrical input power, or rate of flow of energy, can therefore be expressed by

$$vi = Ri^2 + Li\frac{di}{dt} + i^2\frac{dL}{d\theta}.\omega \tag{5}$$

However, the stored magnetic field energy is given by

$$W = \frac{Li^2}{2}$$

and so (with L and i both functions of time) the rate of change of magnetic field energy is given by

$$\frac{dW}{dt} = \frac{d}{dt}\frac{(Li^2)}{2} = Li\frac{di}{dt} + \frac{i^2}{2}\frac{dL}{d\theta}\omega$$

Therefore Equation 5 can be rewritten as Equation 6.

$$vi = Ri^2 + \frac{d}{dt}(\frac{Li^2}{2}) + \frac{i^2}{2}\frac{dL}{d\theta}.\omega \tag{6}$$

The three terms on the right hand side of Equation 6 can be identified as follows. The first is the power loss in the coil resistance. The second is the rate of increase of stored magnetic energy and the third is the power converted from electrical form to mechanical output power.

The mechanical output power in watts is the product of the torque in newton-metres and the speed in radians/second. It follows from Equation 6 that the torque developed at any instant is given by

$$T = \frac{i^2}{2}\frac{dL}{d\theta} \tag{7}$$

i.e. the torque, by this simplified analysis, is proportional to the square of the current and to the angular rate of change of inductance.

The torque/angle curve of Figure 7b can now be calculated from the inductance curve of Figure 7a. At a constant coil current, the torque has a constant positive value over the region where the inductance is rising with angle at a constant rate (θ_0 to θ_1). It is zero where the inductance is is constant (θ_1 to θ_2) and (θ_3 to θ_4), and has a constant negative value where the inductance is decreasing uniformly (θ_2 to θ_3). The pattern repeats cyclically, for the motor of Figure 6, twice in each revolution.

For this motor to run continuously, developing a positive mean torque, the current should be switched on during the positive torque-producing period and be switched off where the torque would be negative. Hence the need for an encoder to enable the control electronics to operate the switches at the required angles.

For the motor to run in the reverse direction, the coils will again be excited when the inductance is rising with rotation. In terms of the power flow of Equation 6, electrical power is supplied over the period when $dL/d\theta$ as well as ω is negative, so that positive mechanical output power is obtained.

It is also apparent from Equation 6 that if the coils are excited with constant current with positive rotation whilst the inductance is decreasing (negative torque), then both mechanical power is being fed into the machine and the stored magnetic energy is decreasing. Then, providing the resistance losses are smaller than the sum of these two, the electrical power being 'supplied' is also negative, i.e. the machine is acting as a generator. This also applies with negative rotation.

It is clear that the machine has the potential to act as a motor or as a generator in either direction of rotation. However, it is obvious from Figure 7b that the primitive single-phase machine of Figure 6 is incapable of starting in either direction as a motor unless it happens to be at rest in either of the regions θ_0 to $\theta_1$or θ_2 to θ_3. The solution is to add more phases, so that at least one phase is in a torque-productive region for the required direction of rotation at any initial position. Two-phase motors can be designed to start from any initial position in one direction only; three or more phases allow starting in both directions. Figure 5 showed a 4-phase machine. The question of starting capability and phase number will be discussed further in Section 3.

2.3.2 Excitation schemes and current waveforms

The explanation of torque production above assumed that a constant current could be established whilst the rotor moved through a negligibly small angle, could then be held constant over the required angle of changing inductance and then be removed whilst the rotor turned through a negligibly small angle. In practice this can be approximated very well when the rotor is turning slowly, i.e. at low speeds.

Consider low-speed operation of the system shown in Figure 5. A typical chopping current waveform is shown in Figure 8a. Current is established in a phase winding by closing switches S_1 and S_2. The current rises rapidly to the desired level under the influence of the applied voltage V_s. If S_1 and S_2 are now opened, the stored energy in the magnetic field (i.e. in the inductance) ensures that the current must continue to flow through the only available path, through D_1 and D_2. The voltage now impressed on the winding is $-V_s$ and the current falls and during this time some magnetic energy is being returned to the supply and, in the rising inductance region, some is being converted into mechanical output. When a lower specified current level is reached, S_1 and S_2 are closed and the current rises again. At the end of the required phase conduction period, both switches are turned off and the current falls to zero. Torque is controlled by varying the level at which the current is chopped. This is only one of a number of methods of chopping control; more detail is given in Section 4.

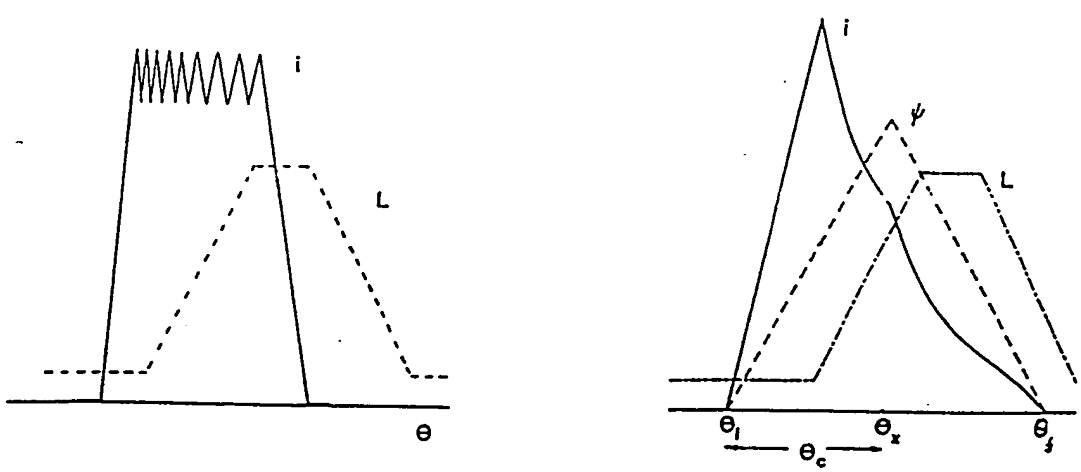


Figure 8 (a) (b)

It will be clear that as the speed of rotation rises, the times required for the initial growth and final decay of current correspond to increasing angles. The result will be a loss of torque, for a given chopping level, at higher speeds. The condition can be alleviated by operating the switches in advance of 'natural' points defined by region θ_0 - θ_1 in Figure 7. This introduces two new and important control variables, i.e. the switch-on and switch-off angles, but the machine is still operating in the 'current-fed' mode.

At even higher speeds, the rise and fall times for the current will be such that the current is switched on and off only once in each conduction period and is never chopped. The machine is now voltage-fed (i.e. the current is not regulated by chopping) and torque is controlled through the switching angles. This is the so-called 'single-pulse mode' of operation.

Figure 8b shows single-pulse waveforms of current and flux (in accordance with Equation 4). The winding is switched on at some angle θ_i, **in advance** of the onset of the rising inductance region. The effective inductance of the circuit is L_{min} initially, so allowing current to build up rapidly before the start of the torque-productive region and so to maximise its torque-producing effect. The rising inductance (and the resulting motional emf) then causes the current to rise less rapidly, or even to fall, as in Figure 8, when the motional emf is greater than the supply voltage. The switch is opened at some angle θ_x, typically before the maximum inductance is reached and the current falls rapidly because an opposing polarity of voltage is impressed on the winding by virtue of the current flowing into the supply through the diodes. The current reaches zero at θ_f. The angle between θ_i and θ_x is called the 'conduction angle' θ_c. This angle is of considerable importance for the control of the machine.

The simplicity of the waveform of flux linking the winding is particularly interesting. For negligible resistance, as long as positive constant voltage is applied, the flux increases at a constant rate (see Equation 1) and, conversely, when a constant negative voltage is applied, the flux decreases uniformly. The maximum flux always occurs at the instant of switch-off defined by θ_x. Figure 8b shows a flux-linkage waveform in the voltage-fed, single-pulse mode. The volt drop across the winding resistance and the switches is assumed here to be small compared to the supply voltage. In all but very small motors, this assumption is normally justified and the well-conditioned, triangular waveform enables the flux waveforms in different parts of the machine's magnetic circuit to be found directly (see below).

The single-pulse waveform when generating can be readily shown to be the same as when motoring (e.g. Figure 8b), but with the direction of travel along the θ axis reversed. Referring to Figure 8b, the winding is switched on at θ_f as the inductance is rising. It is switched off at θ_x and falls to zero at θ_i. (The current rises after switch-off in this illustration because the motional emf is greater than the supply voltage and is now in the sense to drive currents through the diodes back into the supply.)

The concept of the voltage-fed, single-pulse operation is extremely important for the design of SR drives. Historically, the design philosophy of stepping motors was based on open-loop, current excitation for optimum high-torque, low-speed stepping. In contrast, the objective for the Authors and their colleagues in developing the SR drive was a wide-speed-range, high-

efficiency, well-controlled drive, which was capable of exploitation up to very much higher powers than stepping-motor technology. A new approach was called for and it quickly became apparent that the optimum use of voltage-feeding with switching-angle control was very important for minimising the VA requirement of the converter, maximising the system efficiency and minimising the converter cost, i.e. for achieving the best total system design (see Refs 1 and 2).

2.3.3 Basic characteristics

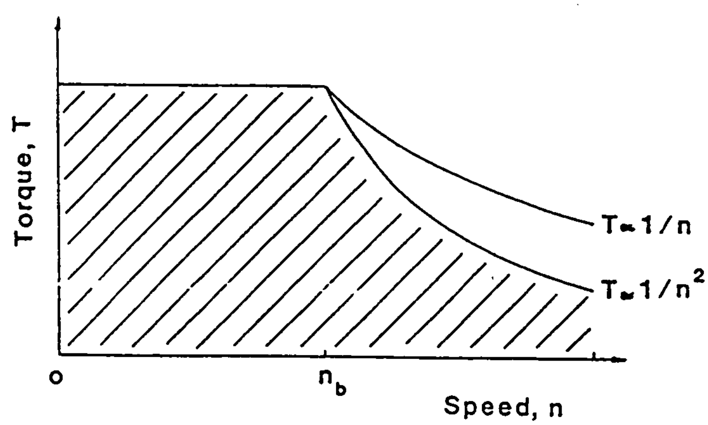


Figure 9

The basic torque/speed characteristics for the SR drive can now be established. These are illustrated in Figure 9. At low speed, the current is controlled by chopping at, say, its rated value, giving a constant torque as the speed rises. This torque can be maintained, using angle control, through a region of single-pulse operation, up to the base speed, n_b. Above this speed, if the angles are held constant, the flux magnitude falls linearly with rising speed. Assuming magnetic linearity, the torque will fall in this region as $1/n^2$ and the power by $1/n$. (This is the well known 'series' characteristic, illustrated in Figure 2, and it is the 'natural' uncontrolled, voltage-fed characteristic of the SR motor.) The torque can, of course be controlled at any speed within the area shown, by either chopping or angle control, or a combination of the two techniques. (Other control strategies will be discussed in Section 4.)

By appropriate design for the base-speed condition, the necessary degree of flexibility of angle control can be designed into the system to enable angle control above base speed to be used to keep the fall in flux approximately proportional to $1/\sqrt{n}$ and the torque to $1/n$, giving a **constant power** characteristic above base speed (see Figure 2).

2.4 Conclusions

A general survey has been given of the common characteristics of electrical drives, as background to a discussion of the SR drive capabilities.The basic principles and features of the SR drive have been described. A simplified, linear analysis of torque production in the SR machine has been given and the principles of control have been established, leading to the 'natural' drive characteristics.

Section 3 will give a more detailed and rigorous treatment of the SR machine.

3 SR MACHINE DESIGN AND ANALYSIS

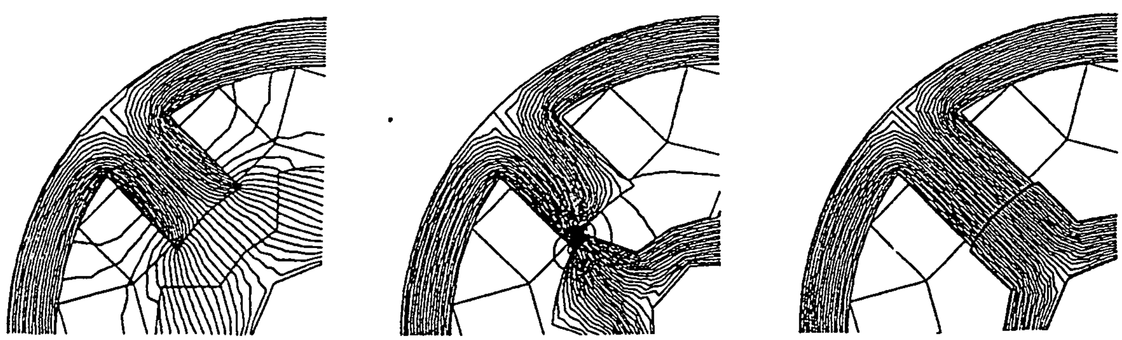
3.1 Introduction

Having described the constituent parts of the SR drive and having established its basic modes of operation through a highly idealised analysis, it is now appropriate to proceed to a more thorough understanding of its behaviour and of the elements of machine design. This is covered in this Section, firstly by examining the nonlinear magnetic behaviour of the machine, then by discussing how it can be modelled, and finally by considering the most important design options.

It may seem strange to the reader to be giving such prominence here to nonlinear magnetic behaviour. Magnetic saturation does not play a prominent part in the understanding, or even at the first-order level, in the design of the common electrical machines. For example, saturation can be allowed for by the use of 'effective values' in otherwise linear equivalent circuits. The SR motor is different. It will be seen below that saturation effects have a significant effect on machine behaviour, not only when it is working hard, but even at modest loads. Linear analysis is useful for a first level of understanding, but gives a totally false impression for machine design purposes and even for the detailed design of power converters.

3.2 Nonlinear Magnetic Behaviour

3.2.1 Local and bulk saturation and fringing



(a) (b) (c)

Figure 10

Finite-element plots, such as those shown in Figure 10 are useful in building up a picture of the behaviour of the flux in the doubly-salient magnetic structure of an SR machine. Comparison of the three figures shows how the flux distribution varies as the rotor rotates. All three are computed for the **same excitation current**, but the three figures do not correctly show the relative flux **densities**, because they have been drawn with the same number of flux lines. Because of the decreasing effective airgap as the rotor moves from the misaligned position (Figure 10a) to the fully aligned position (Figure 10c), the flux for a given current increases and the resulting pole body flux densities are respectively in the ratios

0.06/0.34/1.0.

Several important features are clearly visible:

i) The effective airgap at the unaligned position is large and it would therefore be expected to dominate the reluctance of the magnetic circuit in this position.

ii) In the misaligned position, much of the flux does not cross the airgap radially. (In this respect it departs from the simplistic assumptions of Section 2.) It follows that, as the rotor moves in either direction, the flux will increase as the stator and rotor poles approach each other, i.e. before the poles start to overlap. This non-radial airgap flux is loosely called 'fringing flux'.

iii) For small overlap angles, the flux concentrates at the overlapped pole corners, and the steel would be expected to saturate in this region even though the total flux and the density in the main parts of the magnetic circuit are low. This is called 'local saturation'

iv) The flux, for a given excitation, increases with overlap and reaches its maximum in the fully-aligned position. The magnetic circuit is then a classic one with a small airgap. It should be possible to apply conventional magnetic circuit analysis, and the usual form of saturating manetisation curve should result.

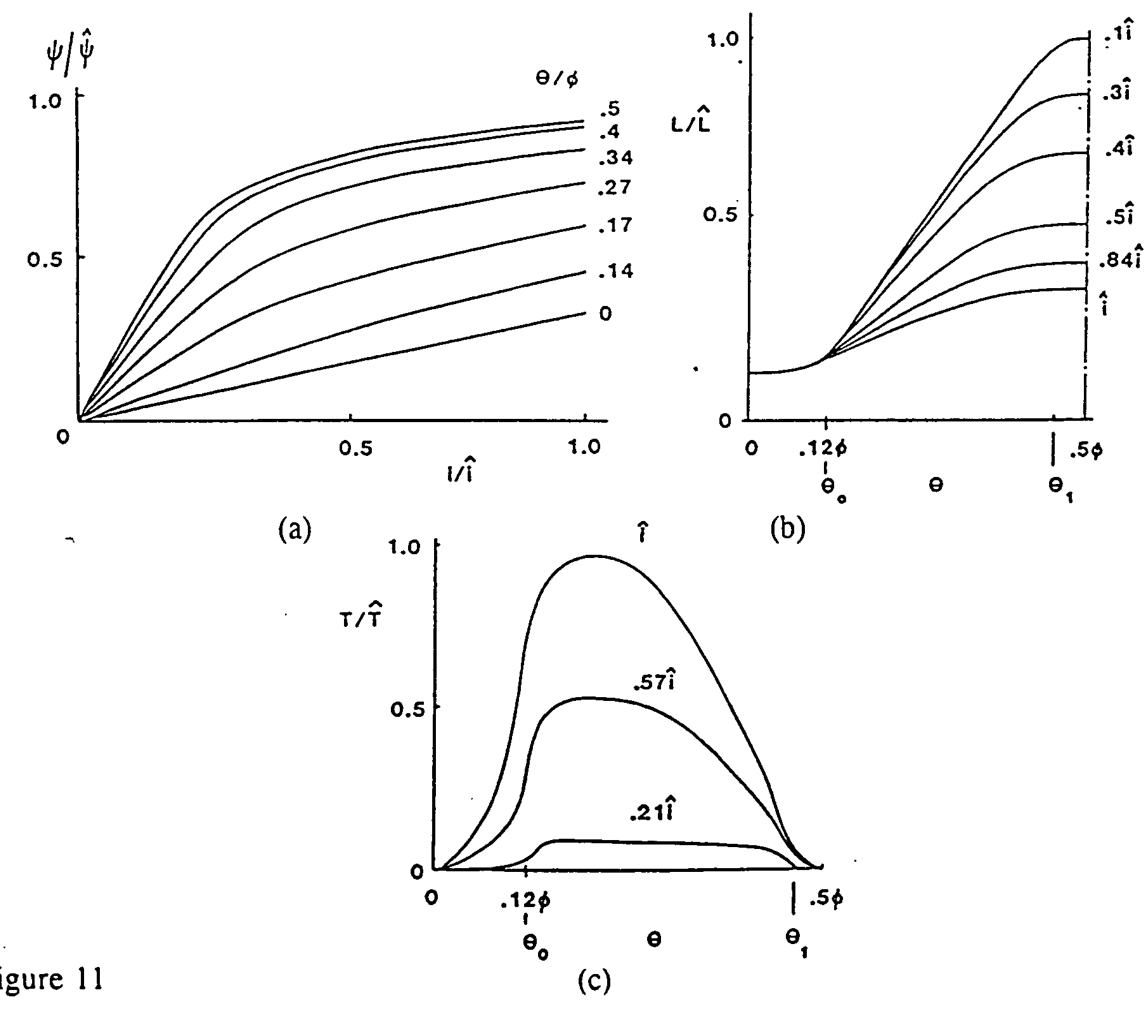


Figure 11

The overall properties of this complicated magnetic field behaviour are succinctly expressed in a set of characteristics of the form of Figure 11a, b and c. These show typical normalised curves of flux-linkage with current at different angles, and inductance and torque with angle at various currents. All three figures show very marked departures from the ideal behaviour assumed in the simple analysis of Section 2. The angle of rotation of the rotor, θ is normalised to the angular pitch of the rotor poles, ϕ. This angle corresponds to one cycle of a phase inductance variation, i.e. L_{min} through L_{max} to L_{min} again. Phase inductance is normalised to the maximum inductance. Flux linkage, ψ, is normalised simply to a notional highly saturated value.

Looking first at Figure 11a, it is seen that the ψ/i curves are nonlinear, showing evidence of saturation at all angles other than the misaligned position (θ=0). Bulk saturation effects can be observed best for positions with full overlap between stator and rotor poles ($\theta=0.5\phi$), when there is no influence of local saturation. It can be seen from the curve for $\theta=0.5\phi$, that bulk saturation occurs at all normalised flux-linkage levels in excess of 0.5. Local saturation can be clearly separated from the bulk effect below this flux level. It is best observed at small values of overlap, e.g. in the nonlinearity of the ψ/i curve for 0.17ϕ.

The most striking features of the inductance curves of Figure 11b in comparison with the ideal curves of Figure 7a are the very great variation of inductance with current (see especially maximum inductance) and the absence of sharp transitions as the poles start to overlap at θ_0 and become fully overlapped at θ_1. The flux rises before θ_0 due to fringing and therefore so also does the inductance; it is substantially independent of the current. The amount of fringing flux decreases as the fully overlapped position is approached and the rate of rise of inductance decreases.

The torque curves of Figure 11c also show a big departure from the ideal of Figure 7b. The existence of torque before the start of overlap at $\theta=0.12\phi$ is due to increasing fringing flux as the pole tips approach each other. The large loss of torque at large overlap and high current is due to bulk saturation. The effect of the strong interaction between local saturation and fringing flux is very plain from the changes in torque/angle profile with current in the region before overlap.

3.2.2 Influence of saturation on energy flow

The relationship between the stored magnetic energy and that converted into mechanical output is easily seen from a study of a trajectory on the ψ/i charateristics.

Figure 12a shows a set of typical curves, together with an ideal current trajectory, *OabO*. A current is established in the minimum inductance position, along the line *Oa* and is held constant until the aligned position is reached at *b*, when it is reduced to zero along the line *bO*. This is an ideal low-speed chopping trajectory.

The area *OabcO* represents the the energy taken in from the supply as the rotor moves from the misaligned to the aligned position. The area *OabO* represents the amount of energy converted into mechanical work, and *ObcO* represents the magnetic energy stored at the aligned position, just before the current is reduced to zero. This stored energy must be

dissipated, or more usually, returned to the supply, resulting in a circulation of energy between the machine and the power converter. It would be beneficial to the system to minimise the circulation of energy, with its associated increased device currents and losses. Ideally, the ψ/i curve in the aligned position would follow *Ocb* rather than *Ob*.

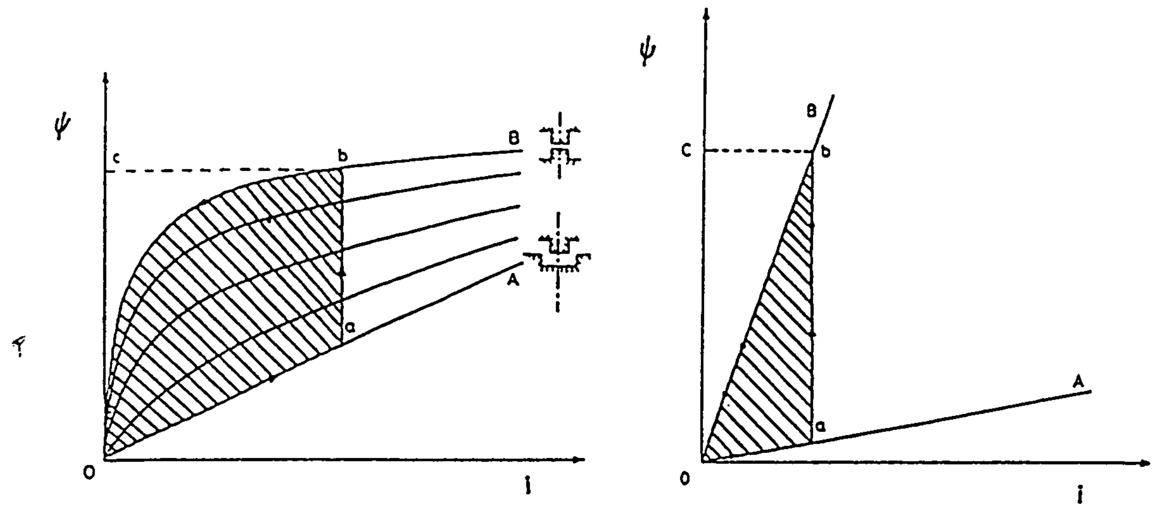


Figure 12 (a) (b)

This reasoning, applied to a comparison of an ideal non-saturating steel (Figure 12b) with the ideal saturating material, has given rise to an extensive debate on the virtue of saturation. Reference 3 is suggested for access to the literature. Some authors have claimed that saturating steel enables up to twice as much output to be obtained from a machine than from one using non-saturating steel. However, it is argued in Reference 3 that these arguments are fallacious because they force the non-saturating steel artificially to conform to the maximum flux density of the saturating material.

The important practical conclusions of this debate are that :

(i) The best steel has as high a permeability as possible, with as high a saturation level as possible.

(ii) The aligned airgap should be as small as practicable.

(iii) Saturation, when it inevitably limits the flux, should do so in the airgap region and not in the parts of the magnetic circuit remote from the airgap.

3.2.3 Practical flux waveforms

The fundamental nonlinearity of the magnetic characteristics of the SR machine makes it difficult to keep a clear picture of the interactions of the many design variables. In this situation it is very helpful to be able to hold on to one very simple and basic relationship in machines with reasonably low winding resistance in the single-pulse mode. This is the behaviour of the flux linkage, which, as has been seen in Figure 8b, follows a simple

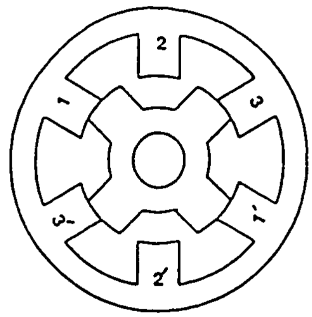


Figure 13

triangular variation. A knowledge of the waveform of the phase flux linkages enables the flux variation in any part of the magnetic circuit to be deduced easily. This will be illustrated with reference to the three-phase, 6/4-pole machine shown in Figure 13. In this machine the winding connections are such that when the phase windings 1,1', 2,2' and 3,3' are excited, the resulting polarities of the poles, starting with pole 1, are NNNSSS.

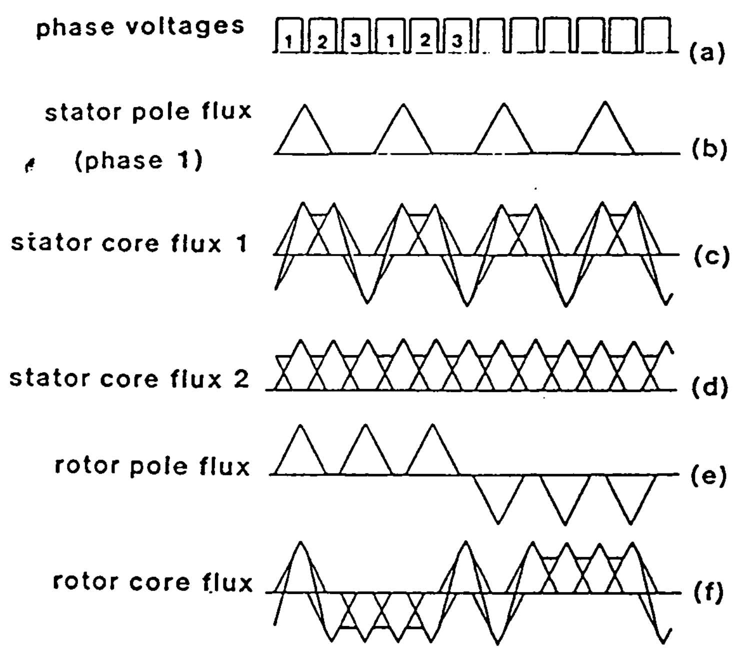


Figure 14

Figure 14 shows the construction of the flux waveforms in the regions of the magnetic circuit. (This figure is reproduced from Reference 2.) The sections between the centre lines of poles 1 and 2, 2 and 3, 1' and 2', 2' and 3' will have flux waveforms as shown in Figure 14c.

The waveform is made up of a triangular component of fundamental frequency f_{ph} and a constant component, the sense of which depends on the particular section of magnetic circuit. The remaining sections, i.e. between the centre lines of poles 3 and 1', 3' and 1 have the type of waveform shown in Figure 14d, which has a constant component with a fundamental 'ripple' component of frequency $3f_{ph}$ .The poles of the rotor experience reversal of the triangular flux 'pulses' twice in each revolution, as shown in Figure 14e. The rotor core has

the waveform of Figure 14f.

Clearly this method of building up the flux wavefoms in the voltage-fed mode is powerful and can be applied to any winding for any phase number or pole number.

There have been many examples of workers on SR machines being led into error by a failure to keep a clear picture of the flux behaviour. A simple example of the clarity offered of behaviour in the single-pulse mode is the relationship between supply voltage and winding turns. If the number of turns is changed proportionally with the supply voltage, then with the same switching angles at the same speed, the flux variations **throughout the machine** will be unchanged no matter how saturated the steel. The torque and power will also be unchanged.

As another example, if the supply voltage is reduced proportionately to the speed, other things being unchanged, then the flux and the torque will be unchanged.

It is also helpful to picture the torque as being produced by the airgap **flux** rather than in terms of current. In general, the applied voltage impresses a flux on a varying magnetic circuit and **the current in the phase winding is that which is necessary to give the mmf to support the flux through the magnetic circuit**. For example, a linearly rising flux caused by a constant applied voltage, will give rise to a variety of complex current waveshapes depending on the rotor position, speed and saturation level.

With the basic understanding of how the SR machine works now established, attention can be directed to designing machines. It is first necessary to be able to predict the parameters of a proposed design and then to be able to predict the performance. These topics are addressed in the next two Sections.

3.3 Parameter Prediction

The whole magnetic character of the SR machine is enshrined in its $\psi/\theta/i$ curves, and any practical design method must include a prediction of these curves so that changes in core proportions or windings can be studied.

The calculation of flux linkage as a function of current at the aligned position is easy because the geometry is that of a classical small-airgap magnetic circuit.

The determination of the same relationship at the fully misaligned position is more difficult, even though the geometry is symmetrical. This is because of the large airgap. (Figure 10a shows the resulting field.) The basis for a very effective analytical method for predicting the ψ/i relationship, based on a sketch of the flux lines, is given in Reference 4. However, this work emphasised the importance of recognising the three-dimensional nature of the field in this rotor position if satisfactory accuracy is to be achieved. Two and three-dimensional numerical field solutions confirmed this [5]. More recently, a number of workers have applied finite-element methods to the field in the SR machine [6,7,8,59,60,61,62]. It is the Authors' experience that the speed of solution is now such that a finite-element method can be used routinely for two-dimensional solutions in the misaligned position (with a correction for the effect of the third dimension), as confirmation of the quicker analytical method.

Having predicted the $\psi/\theta/i$ curves at the aligned and misaligned positions, it is still necessary to predict the curves for intermediate rotor positions. Two-dimensional, finite-element methods can be used, but these are not economically viable for routine design in which repeated changes of proportions have to be studied for design optimisation. It seems inevitable therefore that some form of empirical curve synthesis between the maximum and minimum inductance positions must be used. A number of workers have published methods for doing this [38,39,63,64], but SR Drives Ltd have not yet felt able to make their own method public.

Virtually all models used so far neglect inter-phase coupling due to mutual fluxes and common magnetic circuit interactions. This is a reasonable assumption for most machines and operating conditions. However, the modelling of the mutual interactions has recently received some attention in the literature [9,40,41,65].

3.4 Performance Prediction

Having characterised the machine, the data can now be used to find the flux, current and torque in the steady-state for any supply voltage, switching circuit, switching strategy and speed. Methods of solution reduce to a time-stepping solution of Equation 3. Of the various formulations, the Authors' method for the direct solution for the flux linkage [10] seems to be established as the best choice and has proved itself in a very large number of designs by SR Drives Ltd. The torque at any current and angle is evaluated from the well-known Equation 8.

$$T = \frac{\partial W'(\theta,i)}{\partial \theta} \tag{8}$$

where W' is the co-energy of the system, represented at any operating point by the area under the appropriate ψ/i curve. The average torque is found by evaluating the enclosed area in the ψ/i plane for one complete cycle. Pulle [42] has published a development of this method, making use of spline functions to model the nonlinear characteristics.

Successful system design can depend critically on the matching of the machine design to the capabilities of economically available switches, and a model capable of accurate prediction of device currents is essential. The application of computer-aided design methods to SR machine design is discussed in References 11 and 12.

Two papers have addressed the more complex problem of a dynamic model of the SR system [43,44].

3.5 Design Considerations

The design problem is that of total SR system design, involving interaction of control, power electronics and machine. Many designs are specific to an application and a detailed design depends on the required characteristics, method of control and the chosen converter topology. Only the principal elements of machine design are discussed here.

3.5.1 Specification

The optimum motor design can only be produced if the requirements are clearly specified. This may be tightly drawn up for a specific application (e.g. a washing machine motor), or arrived at with compromises for a general-purpose drive. In either case the specification will cover such items as: supply voltage range, continuously rated torque/speed characteristic, required overload characteristic, duty cycle, starting requirements, direction(s) of rotation, braking and control requirements, dynamic performance, temperature rise, ambient conditions, enclosure/mounting, cooling system, other special constraints such as efficiency or noise.

3.5.2 Phase/pole/tooth numbers

Basic design choices are the number of phases and, for each of these, the number of stator and rotor poles and, in some cases, the number of teeth per stator pole. There are a large number of possibilities and the choice depends on many factors, including total system economics, but a broad overview is given below.

Three machines with different phase numbers have already been illustrated: Figure 5 showed a 4-phase, 8/6-pole geometry; Figure 6 a primitive 1-phase type; and Figure 13 showed a 6/4-pole, 3-phase machine. All these have a 'two-pole' flux distribution (one north and one south stator pole per phase), which is the form most discussed in the literature. Both the three and four-phase motors are capable of starting from any initial position in either direction, and the choice between them is a matter for detailed examination; both types are used commercially. Reference 2 gives an analysis of the constraints on the choice of stator and rotor pole arcs and possible pole combinations to meet the starting constraint. Higher phase numbers than four have been advocated on the grounds of reduced torque ripple [13], but there is an increase in the cost and complexity of both the motor and the converter.

Clearly multiple-pole combinations of the above basic combinations are possible, e.g. a 'four-pole' version of the basic 6/4-pole, 3-phase machine has 12/8 poles. The switching frequencies at a given speed will obviously increase with the pole number multiplier. It has proved surprisingly difficult to derive a satisfactory analysis for comparing the properties of varying pole numbers for design purposes, but a recently produced study [48] has attempted to throw some light on the matter. (A range of industrial motors using these higher pole numbers will be described in Section 4.)

Hendershot has explored the use of 'double poles' in the context of a novel stator construction, with the object of reducing iron loss in the stator [14]. The Hewlet Packard motor is an interesting example of a motor using more rotor poles than stator poles [15], with the object of achieving low torque ripple and controlled saturation.

Stepping motors have traditionally been designed using multiple **teeth** on each stator pole face and an equal tooth pitch on the rotor. This principle can be used for an SR motor and Figure 15 shows an example of a 3-phase motor with two stator teeth per pole [16]. Simplistic reasoning leads to the conclusion that this type of motor should be much superior to the single-tooth-per-pole types described above; if the same coil can embrace multiple

teeth and if the maximum and minimum inductances are the same as for one tooth per pole, then the torque will be increased in proportion to the number of teeth. The price will be an increase in the switching frequency. However, detailed design shows this attractive conclusion to be severely qualified by a number of factors, including increased minimum inductance and saturation effects. The 'Megatorque' motor is an interesting example of the multi-tooth type, designed to be, effectively, two co-axial motors in one frame [17]. Other examples appear in References 18 and 19.

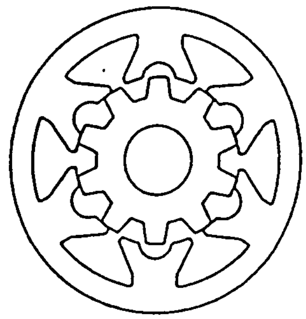


Figure 15

If the requirement for starting from any initial position in either direction is relaxed, two-phase motors can be used. Figure 16 shows a 4/2-pole motor. The rotor pole has been extended and the airgap profiled with a step to give a rising inductance in one direction of

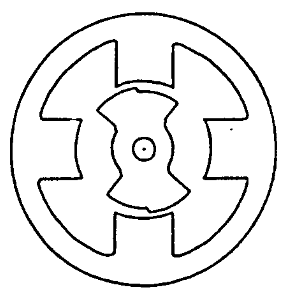


Figure 16

an angle of rotation over 90^{0} to guarantee starting in the clockwise direction[20]. Such machines offer the possibility of a reduced number of switches and a lower switching frequency than those with higher phase numbers. The torque per rms ampere is reduced and may lead to reduced specific output. Byrne [21] described a two-phase motor with the starting achieved by controlling regions of saturation.

If the motor is not required to be able to start from any arbitrary initial position, a single - phase motor can be used. Such motors have been known for many years, using mechanical switching, in such applications as shavers. The electronically-switched (SR) equivalent can be very attractive for a number of applications. Figure 17 shows a recently patented economical form of construction [45]. The back iron between stator poles of like polarity is magnetically redundant in this design. There are a number of ingenious methods for ensuring

that the initial position of the rotor is appropriate for starting in the required direction. The Authors are not aware of any published comparison of the relative specific output of these motors compared with multi-phase types, but the argument of Harris and Miller [22] indicates a lower output capability.

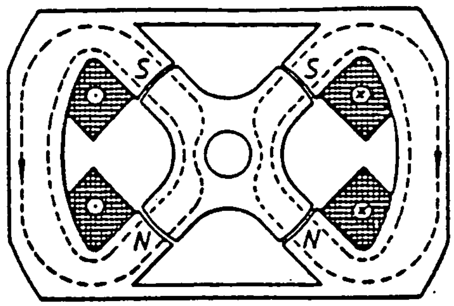


Figure 17

Reference 22 presents a very interesting attempt to analyse the various forms of SR motor in comparison with conventional machines. This is not at all easy, because the doubly-salient pole method of torque production, the vernier action between the stator and rotor poles and the pulsed nature of the excitation make them so different from rotating-field or dc equivalents. The conclusion of Reference 22 is, however, favourable to the SR machine.

3.5.3 Mechanical and thermal design

Good mechanical design and thermal management are vital in achieving a successful design for any electrical machine. Good practice for an SR machine is like that for other types, but, while it is relatively easy to to obtain a lot of torque from an SR motor, it is not obvious how to achieve the optimum motor design, let alone optimum system design.

Mechanically the SR motor is very straightforward and robust. The absence of any electrical conductors or permanent magnets on the rotor makes this component very simple and, incidentally, very suitable for high-speed running. The rotor laminations are usually clamped on the shaft by any of the well-known techniques. Stator construction is straightforward, with a conventionally-built lamination stack and coils inserted onto the salient poles. Normal insulation and impregnation techniques can be used. The short overhang of the ends of the coils and the absence of cross-overs of stator phase windings are particular advantages of the simple stator windings.

The machine housing can be conventional and is determined by the application, ranging from skeleton construction for some domestic appliances, through TEFV frame and forced ventilated frameless industrial types, to explosion-proof housings for the mining industry.

Thermal management is crucial to good design. The losses in the machine arise from copper loss in the coils and from iron loss . It is one of the advantages of the SR motor that most

of the losses occur in the stator, from which they can be removed relatively easily.

For a given machine, the copper loss at any speed depends on the r.m.s. phase current at the particular operating point. This in turn depends not only on the specified torque at each speed, but also strongly on the control strategy and on the magnetic circuit design. This in turn constrains the winding space. The current at the thermally-rated torques will depend on the overall maximum torque-speed profile and supply voltage tolerances. The design strategy may also depend on the selection of economic switching devices for the drive.

The iron losses depend on the basic choices governing the switching frequency (see Section 3.5.2) and on the proportioning of the magnetic circuit, as well as on the type of steel used. For a given motor, the losses are a complex function of speed and load. The flux waveforms are non-sinusoidal (see Figure 14), making iron loss prediction complex. There are a few papers which address the iron loss question in varying degrees [23,24,66,67,68,69].

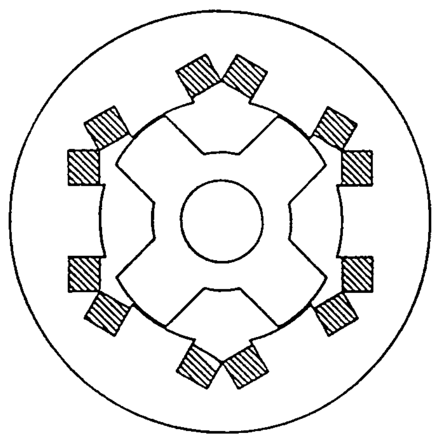


Figure 18

An interesting development in the magnetic and thermal design of SR motors is that of 'projections' on the stator lamination [46], fitting between the coil sides as shown in Figure 18. Such a projecion has the adverse effect of increasing the minimum inductance by the 'slot leakage' effect and also of increasing the maximum inductance in the same way. However, the reduced thermal resistance from coil to core and the increased effective back of core thickness can give a significant overall advantage in many designs. The increased core thickness is of benefit both magnetically and through reduced acoustic noise resulting from the increased mechanical stiffness.

It is clear that the detailed design of the windings and magnetic circuit will depend on the size and speed of the machine and on the cooling system specified. There are no simple answers. Some examples drawn from the Authors' experience will be described in Section 5.

3.5.4 Torque ripple and noise

In the early days of SR systems there was a general expectation that this type of drive would suffer from an acute problem of torque ripple which would cause uneven running at low speeds. This was based on the image of stepping motors drives, which are designed to rotate in discrete steps. The SR drive is designed for smooth rotation, and the low-speed operation has proved to be very good in most applications - given good design.

Torque ripple is unlikely to be a problem at higher speeds, because the torque acts on the system inertia. As the frequency of torque ripple rises with speed, the corresponding speed variation is reduced by the integrating action of the inertia. As an example of the sort of frequencies involved, in an 8/6-pole, four-phase motor there are 24 excitations per revolution and so at 60rev/min the lowest torque ripple frequency is 24Hz; at 1800rev/min it is 720Hz.

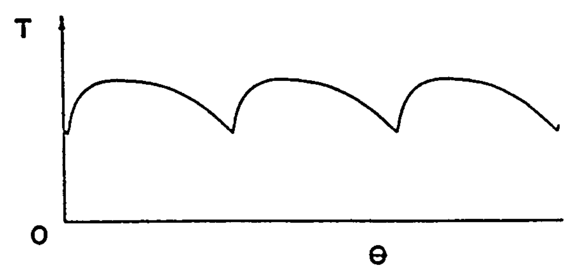


Figure 19

Torque ripple at low speed is a matter for attention (a) where a minimum break-away torque must be guaranteed at any initial rotor position and (b) in applications such as servo systems, where very low speed-ripple at very low speeds is important. In an ideal motor, there would be no torque ripple, as each phase would develop a constant torque with constant current, in turn, with a seamless transition between phases. (See Section 2.3.1.) Figure 11c showed that bulk saturation in a real machine causes a fall in torque at constant current as alignment is approached. Superimposing the characteristics of successive phases (one phase excited at a time) gives a torque/angle curve of the form of Figure 19.

The SR motor has a high peak torque capability and a low rotor inertia and has, therefore, attracted considerable attention as a servo motor. A torque ripple such as that illustrated in Figure 19 would not generally be acceptable for a servo and a number of workers have reported on methods to reduce it. The problem can be tackled on two fronts: (a) by modulating the currents as a function of angle and (b) by modifying the magnetic design to reduce bulk saturation and to reduce the rate of change of torque with angle to ease current modulation. Such modulation using stored profiles has been reported by Welburn[17], Byrne [25], Goslicki [18], and Bent [19]. Egan [26], Wallace [70] and Regas [15] discussed magnetic design. Ilic-Spong [27,28], Matsui [29], Schramm [71] and Wallace [72] have

applied modelling techniques to generate current profiles for smooth torque. Corda [47] has written on the influence of phase and tooth number on torque ripple. These attempts to achieve smooth torque have done so at the expense of specific output. This is an area of active development, with a principal objective of maximising output while minimising speed ripple over a wide range. Work by the University of Leeds and SR Drives Ltd. has achieved very smooth low-speed running with a peak torque ripple of less than 0.05% of applied load at 0.3rev/min in a motor with a high specific output. It is hoped to be able to report more fully on this work in the near future.

Turning to the question of acoustic noise, the SR motor need not be noisy compared with competing drive systems, e.g. inverter-fed induction motors or high-speed universal motors, or even converter-fed dc motors.

Cameron has published a study which includes some very high noise figures, beyond the Authors' experience for similar machines (but note that they were measured close to the machine and not at the standard 1m). He identifies the excitation of the stator natural frequency by harmonics of the stator excitation as the principal source of noise [30]. The Authors have recently been engaged in developments in which improved mechanical design and control strategies have significantly reduced noise. Some examples of noise figures are given in Section 5.

Windage noise is not a particular problem, but the obvious measure of smoothing the airgap profile (by filling in either the stator bore or between the rotor poles) has been used in sensitive cases.

3.6 Conclusions

This Section has endeavoured to provide a sound understanding of the non-linear behaviour of the SR machine, of its modelling and of the principal design considerations.

It will already be clear that there are many design options and interacting variables (magnetic, electronic and mechanical) and that there is no substitute for experience in building up design expertise.

Sufficient references have been included to enable ready access to the published research literature.

The next Section will discuss the power converter and control of the SR drive.

4 THE CONTROL OF SR DRIVE SYSTEMS

4.1 Introduction

The previous sections have considered in some detail the basic principles of operation of the SR drive system and the design of the SR machine. As explained in Section 2, an SR machine must always operate in conjunction with an electronic controller in order to provide a complete drive system. This section will consider in more detail the design and implementation of the electronic controller which, for the purposes of this discussion, is split into two main parts: (i) the power converter and supply sections and (ii) the signal-level control electronics.

Although, for clarity, the power and signal level electronic systems are considered separately in these notes, it is worth stressing again that in a real design, the whole drive would be designed as an integral unit, taking advantage of the many opportunities for beneficial interaction between the electromagnetic design, and the power switching and signal level control design, to produce an optimum system.

SR drive systems have now been designed and built covering a very wide spectrum of power levels and control complexity for many widely differing applications. SR Drives Ltd. has designed systems ranging in power from 10W up to 450kW and carried out design studies into the megawatt region. Control complexity has also varied widely from single-quadrant systems with limited speed-control range, to full four-quadrant high-performance system drive applications. It is beyond the scope of this paper to cover the design of such a diverse range of equipment in depth, but it is appropriate to cover the elements of the control system which are common to all SR drive systems (power and signal level) and to make comments on important points relating to a wide range of power level and control complexity.

4.2 Control Objectives

Before considering the SR drive control system in more detail, it is worth briefly discussing the main objectives to be achieved by the control design.

The primary objective (for motor drive systems) is to provide control of the magnitude and direction of shaft torque. Control of torque must be achieved whatever the rotor position with respect to the stator and whatever the rotor speed or direction of rotation. Of course all drive systems control shaft torque, but most conventional drives have recognised intermediate control parameters, such as armature current in a dc drive, or slip frequency in an inverter-fed induction motor, whereas in the SR drive, torque magnitude is usually controlled directly.

The SR control system must also provide optimum use of all active materials, such that both iron and copper in the machine are utilised to maximum benefit along with the silicon content of the power switches. Other secondary objectives for the torque control of an SR drive may also be required and the following list summarises some normally important objectives.

- Rapid control of torque magnitude and direction.
- Linearity of torque control transfer characteristic.
- Maximum efficiency over a wide torque/speed range.
- Minimisation of power switching and dc link capacitor ratings.
- Stable control of torque with variations in supply voltage, motor temperatures etc.

Having achieved the torque control objective, the design can add a variety of peripheral loops to the system to provide, for example speed control, position control, or many other control parameters according to application. In this respect the SR drive is no different from any other drive system, except that the excellent control provided by the SR torque-control system often allows some remarkable performances to be achieved when under closed-loop control.

When the SR machine is being operated as a generator, the primary control objective will not be shaft torque, but will probably be generated voltage or current.

In general, the controlled SR machine can be viewed in terms of operation from the user's viewpoint, as the equivalent of a fully-controlled dc machine, except that the input to the SR drive will address torque directly, whereas the dc drive will address armature current.

4.3 Power Switching Circuit Configurations

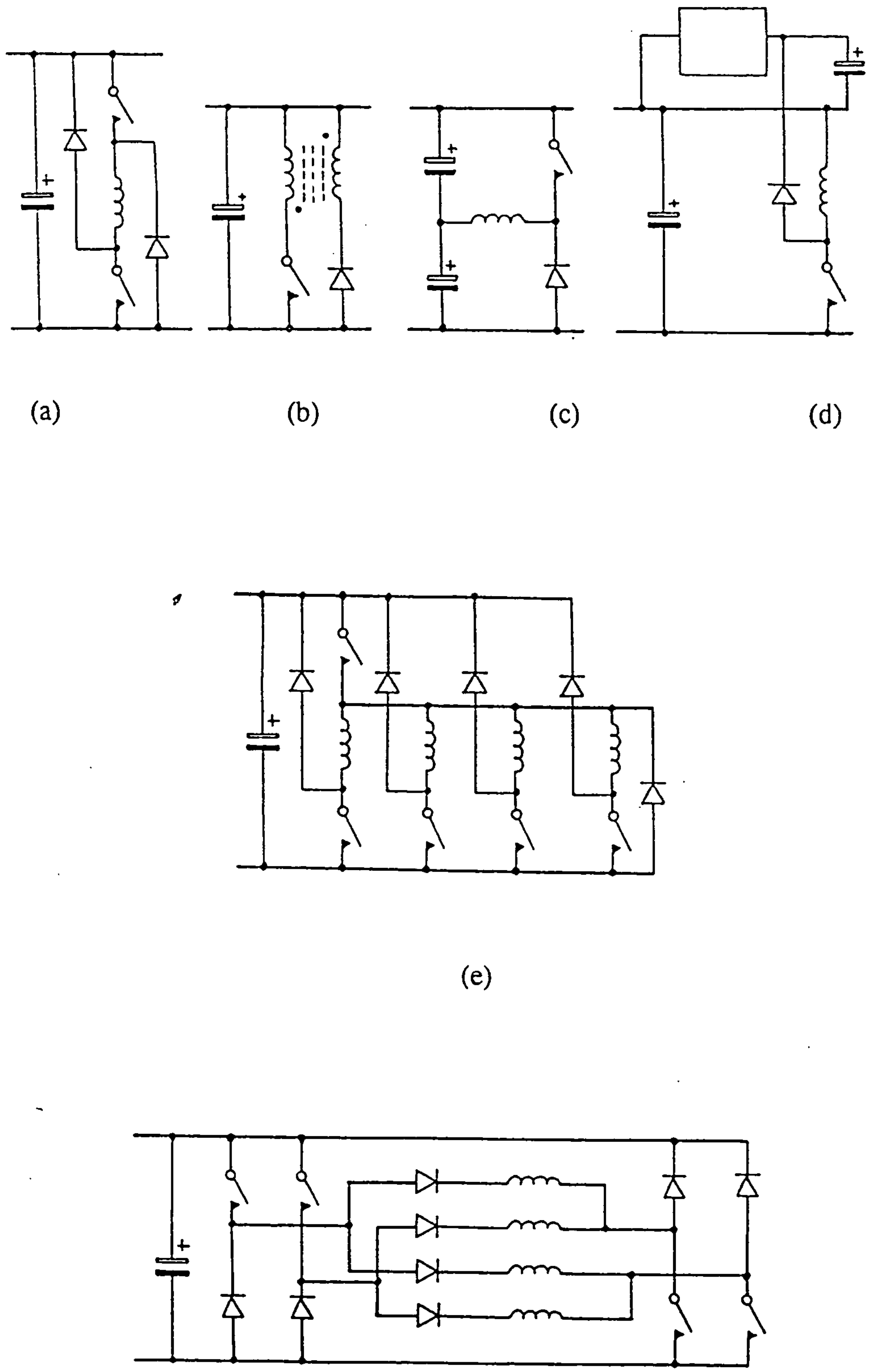
4.3.1 Introduction

The SR power switching converter can take many circuit configurations, unlike variable-frequency inverters, which nearly always use a conventional bridge circuit. This Section will discuss configurations along with some indication of the advantages and disadvantages of the various options.

4.3.2 Basic power converter requirements

The SR power switching converter covers the power electronics between the dc power supply and the SR motor. The basic requirement of the converter is to provide power switching that firstly allows the dc supply to be switched to a motor phase winding, such that flux can build up in the motor pole, and secondly to provide the facility of reversing the voltage across the winding such that the motor flux will collapse. The direction of current in the motor winding is always the same, and each phase circuit requires its own converter circuit.

It will be evident that this basic requirement can be implemented in many ways and the following Sections will describe some commonly used circuits.



(a) (b) (c) (d)

(e)

(f)

Figure 20

4.3.3 Circuit configurations

Figure 20 shows 6 circuit configurations identified as follows:

(a) Two-switch-per-phase circuit.
(b) Single-switch with a bifilar-wound motor.
(c) Single-switch with a centre-tapped supply.
(d) Single-switch with energy recovery or energy dump.
(e) Four-switch, three-phase converter.
(f) Four-switch, four-phase converter.

These circuits have all been described in previous literature as shown in the following references: (a-d) [49,50,51], (e) [52], (f) [53], but a brief explanation of each is given below.

(a) Two-switch-per-phase circuit

This is the most commonly used circuit, since it provides the greatest flexibility of control. When both switches are closed, the dc supply is applied to the winding, allowing flux to build up, and when both switches are turned off the diodes conduct, placing a voltage of reverse polarity across the winding, causing flux to collapse. If only one switch is turned off the current is able to freewheel around the other switch, which gives an approximately constant-flux condition. Although this circuit uses two switches, their voltage rating is only required to be equal to the dc link voltage plus the inevitable safety margin. In addition, no restrictions are placed on the control of an individual circuit, which is often very important.

(b) Bifilar-wound motor

This system uses a single switch, but relies on the transformer action of a bifilar-wound motor to provide the de-fluxing voltage. The leakage inductance of the motor windings imposes a large voltage rating penalty on the switch and the bifilar winding does not allow best utilisation of motor active materials. However, this system can find application at low voltages and low power.

(c) Centre-tapped supply

This circuit can only be adopted for an even number of phase circuits and it requires a centre-tapped dc supply. This can be created by splitting the dc link capacitor but some additional control action is required to maintain the voltage balance. The single switch requires an increased current rating since the effective fluxing voltage is only half the dc supply. Although this circuit has some control restriction, it has been successfully used and was implemented in the Oulton range of SR drives launched in 1983.

(d) Single switch circuit with energy recovery

This circuit uses a single switch to energise the winding, but de-energisation is achieved by allowing the energy stored in the machine to flow into a higher voltage rail, which causes the winding voltage to reverse.

The energy fed into the higher-voltage rail must either be recovered using a dc/dc converter or dumped using resistors. This circuit has control restrictions, but has found application in some areas particularly for low-power, low-voltage systems. Although the system uses only a single main switch, the voltage rating is greater than twice the supply voltage, which is a disadvantage for higher-voltage systems.

(e) **Four-switch, three-phase system**

The previous circuits have illustrated the basic configuration by showing the example of a single-phase circuit, which can be repeated to supply the appropriate number of phases. Some circuit configurations have been optimised for particular phase numbers and the example described here is a circuit for a three-phase system using only four switches [52]. This circuit can perform the same function as the two-switch-per-phase system (*a* above), but does not allow any conduction overlap operation between phases.

This constraint prevents the maximum utilisation of the motor active material, but the circuit can be used in non-critical applications. The low number of switches, combined with only a single switch connected to the upper dc link rail, make the electronic assembly particularly attractive.

(f) **Four-switch, four-phase circuit**

This circuit is another attempt to minimise the number of switches at the expense of some flexibility of control and hence overall drive performance. It has some restrictions in the control of individual phases and uses switches of higher current rating, because of current sharing, but does provide a compact controller for some applications.

Many other possible circuit configurations are emerging [54], which are mostly small variations on the above systems, aimed at optimising a particular parameter or cost element within the drive system. Current-fed SR systems are also beginning to receive attention. It is beyond the scope of this paper to cover all of these possibilities and there is no doubt that further developments will continue to identify new or improved power converter circuits.

4.3.4 Circuit choice

Following a discussion of circuit topologies, the first question which must be addressed is which is the best choice. Unfortunately there is no simple answer. The optimum choice of circuit configuration will depend on many factors including, and most importantly, the performance of the whole drive including the motor. Some attempts to quantify the silicon utilisation in the SR power converter have not taken into account the material utilisation in the machine and its thermal performance, which can lead to misleading results. Cost is often the most important parameter and this must include the whole drive.

Typically, the factors to be taken into account when making the circuit choice include the following:

- Motor phase and pole number.
- Drive cost target.
- Supply voltage.
- Speed range.
- Power level.
- Regenerative operation.
- Physical size constraints.

In the Authors' experience, covering many drive designs over recent years, the circuit configurations *a* and *c* above are most commonly chosen, particularly at higher powers and voltage levels, whilst configuration *d* is a popular choice for low-voltage systems.

4.4 Other Power Processing Elements

4.4.1 Introduction

Apart from the main SR power converter, the complete drive will generally contain other power handling subsystems which, for completeness, should be mentioned here. It is important to note that these peripheral systems are in most cases very similar to those required by any other voltage-fed, electronically-controlled drive.

Figure 21 illustrates the commonly-encountered peripheral systems/components in a full high-performance SR drive system.

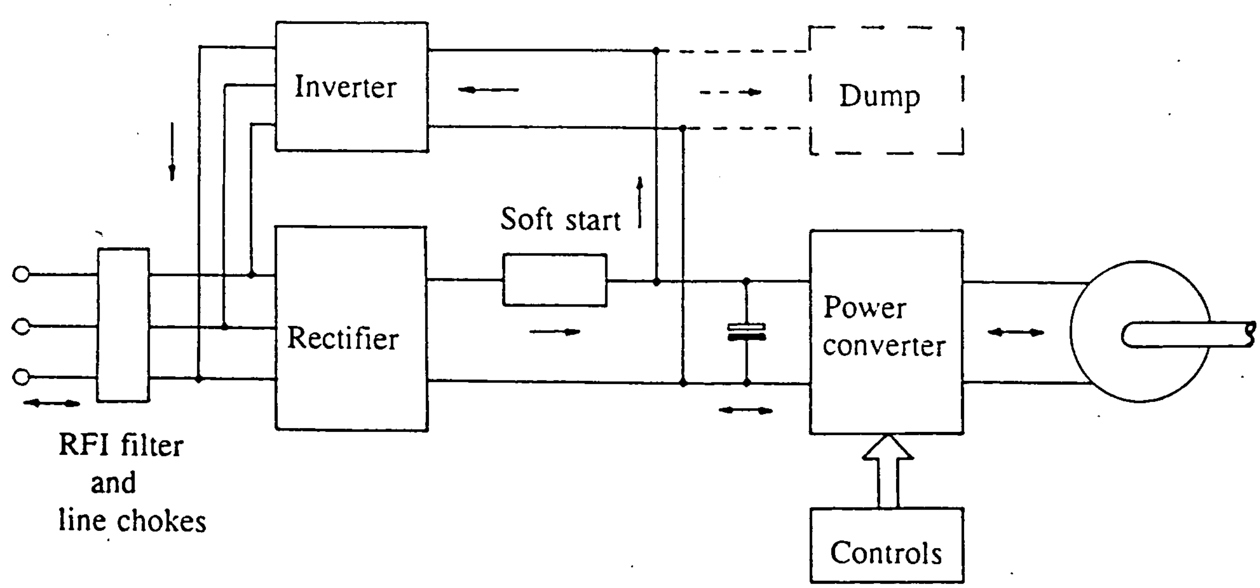


Figure 21

4.4.2 Power supply

The SR drive power converter requires a direct voltage power supply and for mains operated equipment this will be provided by an uncontrolled rectifier with a capacitor to provide smoothing.

The dc link capacitor is also required to carry the ac component of current from the SR power converter. Experience has shown that the SR dc link capacitor is not larger than that required for a voltage-fed inverter, indeed, the SR capacitor is often **smaller**, because a larger voltage ripple can be tolerated on the SR system, since it is not necessary to carefully synthesise an output voltage waveform, as in the case of an inverter.

As with other voltage-fed drive systems, a method of limiting dc link capacitor inrush current is required (soft start) and line chokes are used to minimise harmonics when necessary. RFI filtering will sometimes be necessary in sensitive environments, although generally speaking, the RFI level generated by the SR converter is somewhat lower than that for a PWM inverter because of the lower switching frequency. It should be stressed that the input power factor for the SR power supply will be very similar to that for other voltage-fed drives.

Some developments for small drives will include a power-factor-correction unit, which will provide a stabilised dc link, as well as minimising input harmonics drawn from the supply.

4.4.3 Regenerative operation

The SR drive system can provide braking operation and will regenerate power back into the dc link in the same way as other voltage-fed drives. Under these conditions, energy must be extracted from the dc link in order to maintain a stable voltage level. This can be achieved by:-

(i) Dumping the energy in a chopper-controlled resistor.
(ii) Recovering energy to the mains by means of a synchronous inverter, or by using a bi-directional rectifier.

The only major exception to this choice is when the main power supply is a battery, which can accept regenerated energy directly.

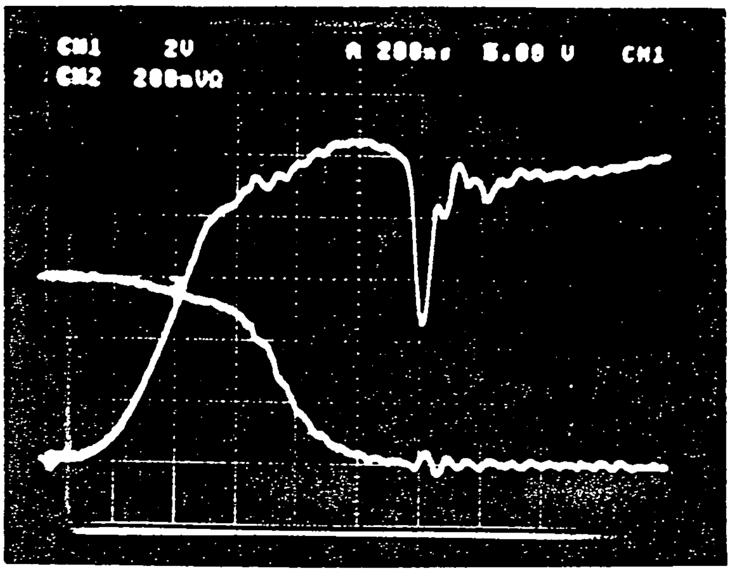
4.5 Power Converter Design

4.5.1 Switching device selection

An important first step is the design of the SR converter is to select the most appropriate power switch for the application. In the Authors' own experience nearly all types of power semiconductor switches have been used for SR drive converters, depending on power level. At present, the choice of devices is usually one of three types, depending on power and voltage level:-

- MOSFET (low voltage to 350V dc link and up to 3kW).
- IGBT (medium voltage to 700V dc link and up to 300kW).
- GTO (high voltage, high power, 2kV dc link, 400kW and above)

In the future, new devices may also become appropriate, such as MCTs, and it is likely that the use of IGBT devices will extend down to lower power, with Mosfets only serving the very low supply voltage applications, eg automotive 12V systems.



V_{CE} = 200V/div

time =.200ns/div

I_C = 200A/div

IGBT turn-off of 600A on 800V dc link.
(1200V, 400A average, device)

Figure 22

Figure 22 illustrates a high-power IGBT switch operating in an SR converter.

4.5.2 Device protection and ratings

As with all power electronic equipment the protection of the power devices takes a high priority in the design process. It will be clear from earlier Sections that all SR converter configurations have a motor winding in series with the power switching devices and this has a major implication on protection, since the classic inverter 'shoot-through' fault cannot exist. In the SR converter the rate of rise of current under fault conditions is modest and therefore no special fast current detection is required and it is not necessary to use device ratings capable of being able to safely handle repetitive shoot-through faults. In some inverters the problem of protection leads to the use of devices of nearly twice the rating of an equivalent SR converter with comparable output.

The complete converter system is protected by over-current, over-voltage and over-temperature circuits, which have proved to be very effective and to provide a very robust converter unit.

The device ratings are predicted by computer analysis of the SR machine performance and it is normal for the peak-to-rms ratio to be about 2:1, which is ideal of Mosfets or IGBTs. The diode ratings are again predicted by computer and will depend on the amount of regenerative braking used. A full four-quadrant drive will require diodes of a similar rating to the main switching devices. The diodes do require a reasonably fast turn-off to avoid large inrush currents when the main switch turns on into a conducting diode, and a soft turn-off characteristic is also beneficial to minimise snubbing requirements.

4.5.3 Integrated power switching

The current trend is to integrate as far as possible the power switching devices into a single module with an isolated heatsink. This technique has many advantages which include:-

- Small peripheral size.
- Lower manufactured costs.
- Reduced interference or inductance loop problems.
- Improved heat transfer.

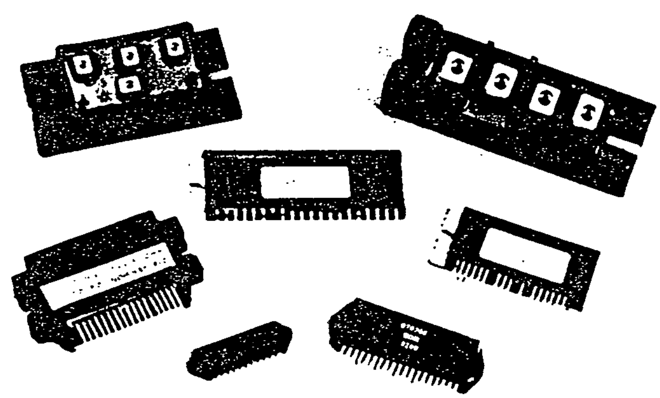


Figure 23

It is often beneficial to design a power switching module to suit particular applications and Figure 23 shows a variety of SR application-specific modules manufactured for SRD Ltd. covering power ranges from 100W to 20kW. Note that the smaller modules contain all of the power switches (Mosfets or IGBTs and diodes) required for the complete drive system, including current sensing resistors. The larger modules contain two switches and diodes and would therefore usually require more than one module for a complete the inverter.

4.5.4 Converter construction and cooling

The construction techniques and cooling methods chosen depend very much on power level, and examples of practical implementations will be shown in the next Section.

In general, layout is very important, as with all power electronic equipment, to ensure that inductive effects are minimised. At low powers, pcb construction with natural cooling is usually adopted. For higher powers, forced air cooling over isolated heatsinks would normally be used. At very high powers, water-cooled heatsinking with GTO devices has been successfully implemented.

4.6 Signal Level Electronic Controls

4.6.1 Introduction

The signal-level electronics has to provide instructions to the power-switching devices to turn on and turn off, such that a continuous and controllable torque is produced at the shaft of the motor. This Section will concentrate on the implementation of torque control, which allows the magnitude and direction of output torque to be addressed by a single input signal. The SR torque-control system uses a feed-forward approach, which allows rapid and accurate control to be achieved. As described in earlier Sections, the control strategy chosen for SR torque control is an important element in achieving optimum performance with minimum overall cost for the drive.

4.6.2 Basic control strategy

In all SR drives the control electronics are synchronised to the rotor movement by some kind of feedback sensor ('rotor position transducer', or'RPT'). This feedback system provides sufficient information to establish which phase winding should be energised to produce the required direction of torque, and when a particular phase ceases to be torque-productive. The control electronics will basically decode RPT signals to provide switching instructions to the power devices.

Figure 24 illustrates the basic control strategy in terms of current waveforms compared to the phase winding inductance/angle variation. As summarised in Section 2, it is necessary to introduce chopping to provide a controlled current limit when the drive is running at low speed and the current chopping level becomes an important control parameter. At higher speeds it becomes necessary to adjust the angles at which the phase windings are energised and de-energised in order to generate the required torque, and when the speed is high enough, current chopping becomes unnecessary and control can be achieved by adjustment of the angular position of the single-pulse current waveform only.

Having established control through the basic parameters of current level and switch-on and switch-off angle, it is necessary to store a map of data which will establish what control parameters are required to give the required output, depending on speed and supply voltage. This control map would normally be stored in an appropriate memory in the control.

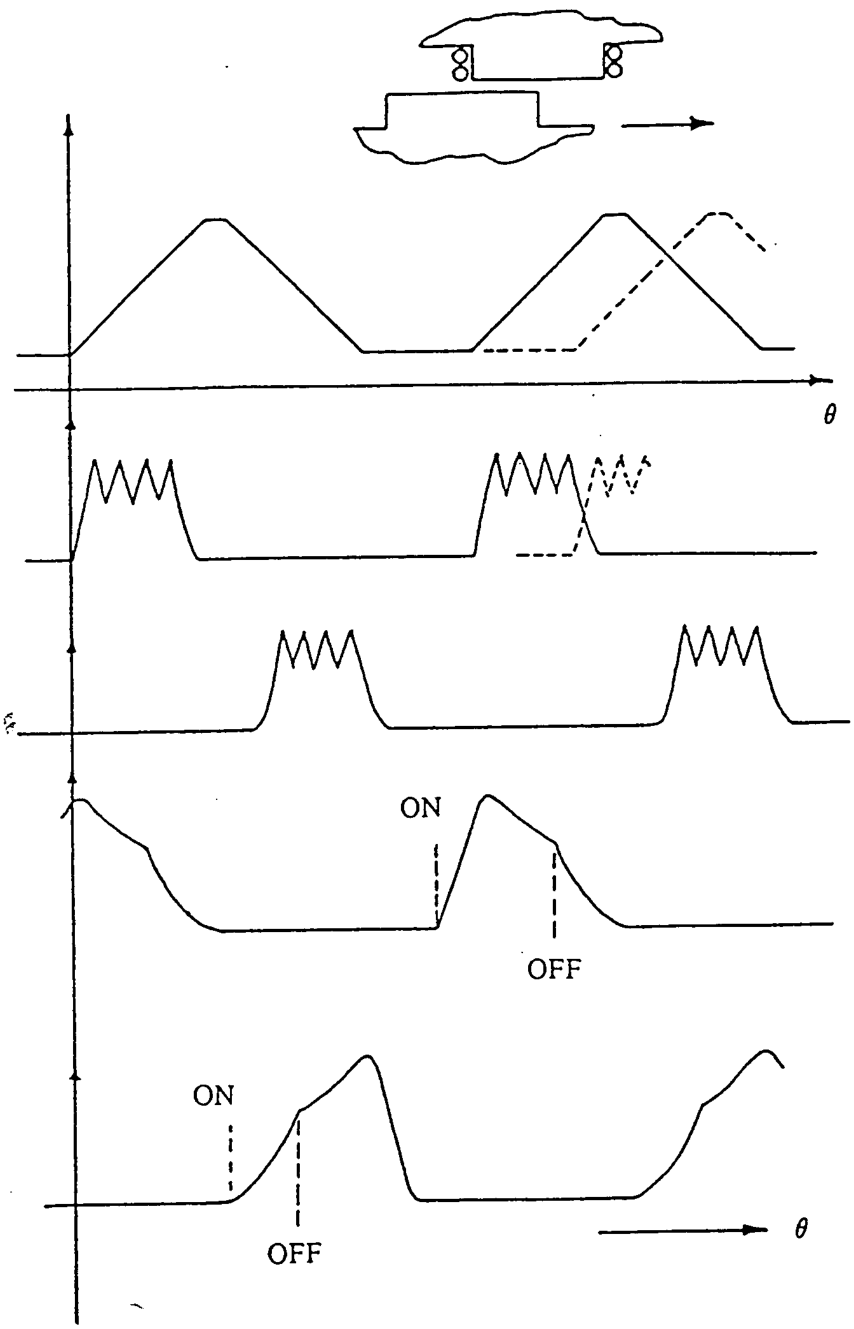
(a)

(b)

(c)

(d)

(e)



(a) Phase inductance (next phase shown -----).
(b) Phase current; chopping; low-speed motoring.
(c) Phase current; chopping; low-speed generating.
(d) Phase current; angle control; high-speed motoring.
(e) Phase current; angle control; high-speed generating.

Figure 24

4.6.3 Digital implementation

In early SR drive systems the torque controls were usually implemented using a hybrid digital and analogue system. Today, however, the torque-control elements use all-digital techniques, normally implemented in an ASIC (Application Specific Integrated Circuit) or gate array. The main elements of a typical SR torque-control scheme are shown in Fig 25.

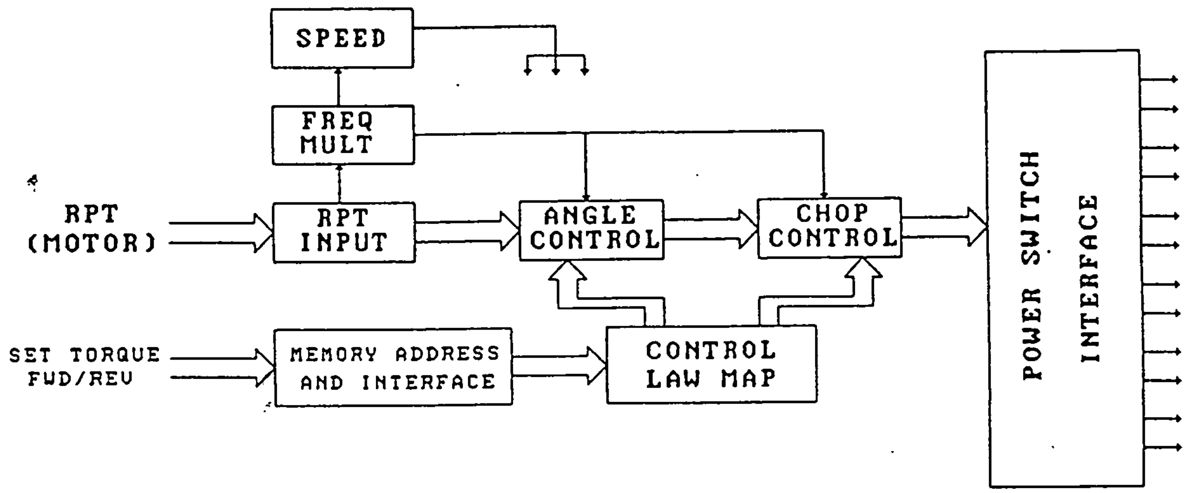


Figure 25

The RPT signals are combined and feed a frequency-multiplier, which generates an angular clock signal, which is used to feed counting circuits in the angle-control section. The angular resolution of the clock may be between 0.1 and 0.5 degrees per bit depending on application. A digital signal proportional to motor speed is also generated for use throughout the control system. The angle control system allows the switching angles to be adjusted, and employs digital counting techniques, controlled by the angle clock. The chopping-control system introduces an adjustable current limit, controlled by current-feedback signals from the power converter.

The motor control map can be stored as a pre-interpolated matrix in an EPROM, or, if a microprocessor is being used on other parts of the control system, it is possible to store a sparse matrix and carry out real-time interpolation in the microprocessor.

When the user demands a torque magnitude level, appropriate switching angles and current levels are selected from the memory, and signals are issued to the power switches through the power interface.

The control system shown is only a very basic form and does not include a variety of secondary control parameters, which may be introduced to enhance performance, such as a freewheeling period for example. In addition, a number of peripheral functions, such as protection and safety interlocks, would also be included.

4.7 Additional Controls and Performance Enhancements

Having achieved a good control of torque, a number of additional controls can be added to provide closed-loop operation or enhanced performance.

4.7.1 Speed control

The most common addition to the basic drive is closed-loop speed control. As with all drives, the speed-loop performance will depend on the quality of the feedback system, and with SR drives, either the RPT-derived signal can be used, or, for higher performance, a separate tacho can be added to the drive. The speed loop would normally include three-term compensation (PID) and the high torque-control bandwidth provides a high closed-loop speed-control bandwidth over a wide speed range with low regulation.

A good industrial SR drive with speed control and tacho feedback would provide, for example, 1000:1 speed range, 0.1% regulation, and 100Hz closed-loop bandwidth.

In many cases the SR drive can match or exceed the closed-loop performance of a high-quality flux vector controlled induction motor.

4.7.2 Position control

A position-control loop can also be added around the speed loop if required. Again the positioning performance of the drive will depend on the accuracy of the position feedback mechanism. It is possible to use the SR motor as a stepper motor for crude positioning and this technique has been successfully adopted for some low-cost actuator systems.

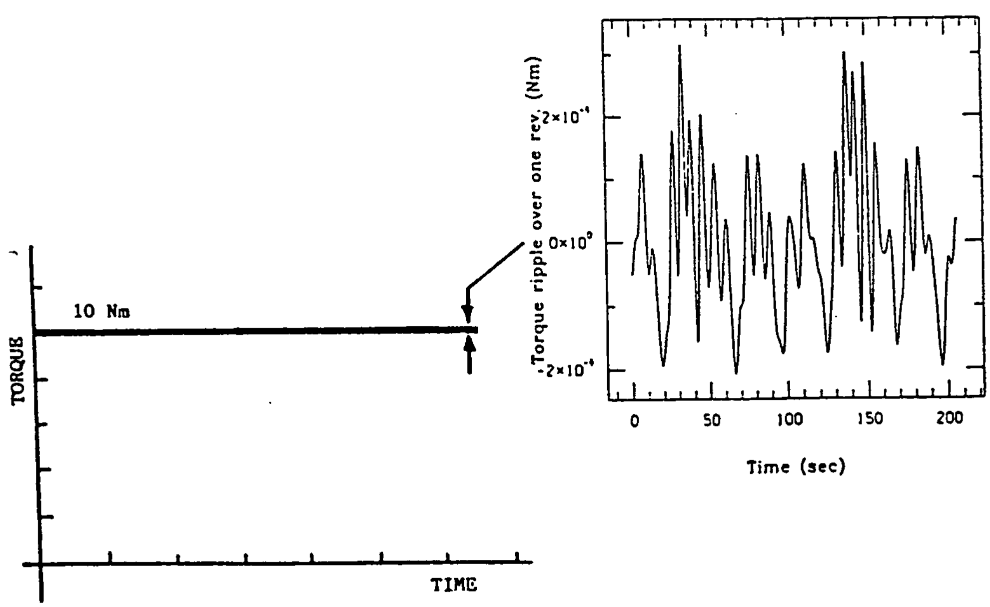


Figure 26

4.7.3 Torque ripple reduction

In the Authors' experience the basic torque ripple of the drive has not caused problems throughout many and varied applications. However, some applications, such as servo systems, would require a low torque ripple and additional electronic controls can be used to reduce torque ripple. This is possible because of the very high torque-control bandwidth of the system, but it is necessary to have more accurate feedback information on rotor position than is provided by the normal RPT. In a recent investigation, using a normal 1500 rev/min industrial drive, the measured torque ripple has been shown to be remarkably low as illustrated in Fig 26.

4.7.4 Acoustic noise reduction

Although several mechanical and electromagnetic improvements have resulted in substantial reductions in acoustic noise, further reductions can be made by suitable additions to the basic control strategy. No details can be given at this stage, since these techniques are the subject of patent applications, but it has been shown that noise level improvements of between 5 and 10dBA have been achieved by small additions to the electronic controls. It should be noted that the changes in the controls do not reduce torque production to any significant extent and do not add any significant cost to the electronics.

Figure 27 illustrates the effect of electronic noise reduction techniques on a front-loading washing machine drive.

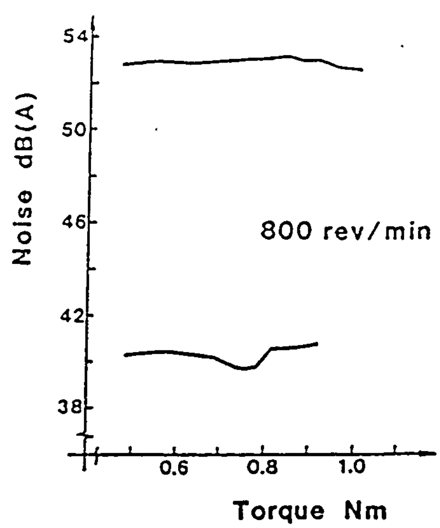


Figure 27

4.7.5 Sensorless position detection

For many applications, a single rotor-position transducer, using Hall-effect or inductive proximity sensors, provides a reliable and cost-effective feedback system. However, some applications cannot allow the use of separate transducers and this has led to a great deal of research into sensorless position detection. (Reference 55 gives an introduction to the bibliography.)

Many techniques have been investigated, all aimed at deriving rotor-position information from the measurements of motor voltages and currents and sometimes the use of diagnostic pulses. It is not clear which technique will emerge as the best, but there is no doubt that sensorless operation is a real possibility for some applications. As the cost of the additional signal processing reduces, these techniques will begin to replace simple transducer systems.

4.8 Practical implementation

Although the whole torque control system can be implemented in microprocessor software, the use of an ASIC has been found to be more cost-effective. Typically about 1500 gates are required to implement the basic torque control systems without enhancements. All of the peripheral systems, such as speed loops and user interfaces, are generally implemented using a microprocessor of sufficient speed/processing power for the application.

The combination of microprocessor and ASIC has been found to be a very powerful and cost-effective method of implementing the whole SR signal-level controls.

4.9 Conclusions

The SR control system has been shown to be simple and flexible to implement with many unique advantages compared to conventional drive systems. The controls have now reached a level of maturity which makes it possible to provide highly-integrated and low-cost control systems, that allow optimum performance to be obtained from the SR motor.

Although the SR controls have now found many applications, the technology still has enormous development potential and further improvements can be expected to emerge over the next few years.

5. APPLICATIONS AND PERFORMANCE

5.1 Introduction

The previous sections of this tutorial have covered the basic principles of the SR drive system and the detailed design and operation of the motor and controls. It is now appropriate to consider the pérformance of SR drive systems using a number of application examples to highlight particular features.

The applications of SR drives are now very diverse and it is difficult to define rigid application areas since there will be much overlap. However, for the sake of clarity in this case it is helpful to consider performance measurements under headings of specific application groups, most of which are from developments carried out by SR Drives Ltd.

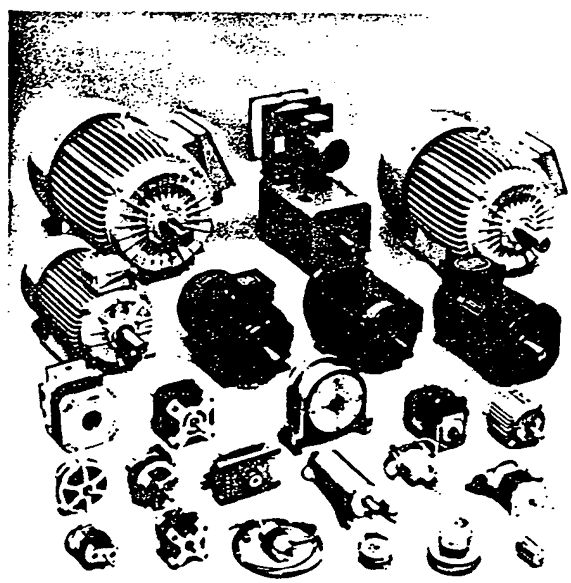


Figure 28

Figure 28 shows a collection of SR motors to illustrate the very diverse applications and power levels.

5.2 General-Purpose Industrial Drive

5.2.1 Introduction

The following section describes some performance characteristics for a range of SR drives that could be described as general-purpose industrial drives. This area covers a very wide range of applications and for the purpose of this discussion, it is divided into three main categories.

- Lower power drives (2-3kW output).
- Medium and high-power to general-purpose drives.
- High-performance (dc type drives).

5.2.2 Low-power drives

The performance of low-power SR drives shows some outstanding performance characteristics compared to small inverter-fed induction motor drive systems. In a recent well -controlled comparative test programme, an SR motor was built using a conventional induction motor frame shell and end brackets, but with about 18% less overall length. This motor was controlled from a Mosfet-based power switching converter supplied by 240V mains and the drive output was compared to published performance figures for the equivalent three-phase induction motor running from a sinusoidal voltage source supply at 50Hz. The results of this comparative test are summarised in Figures 29(a) and 29(b).

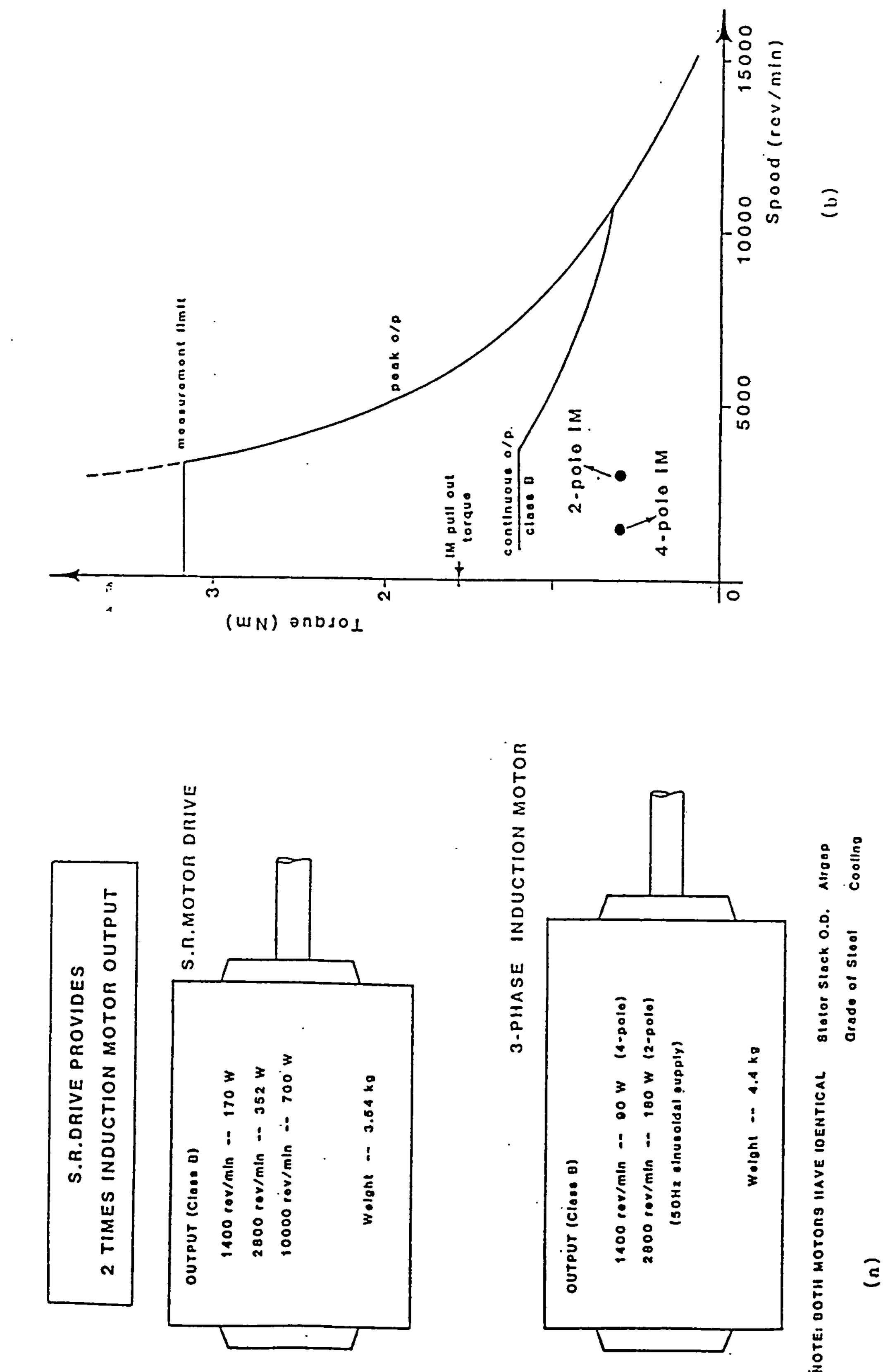
It can be seen that the SR drive output is roughly two times that of the induction motor at 4-pole or 2-pole speeds and the SR drive can also run up to higher speeds to provide higher output powers, for example, 700W at 10,000 rev/min. It should be noted that both the induction motor and SR drive were Class B rated with identical cooling and the same grade of lamination steel and identical radial airgap. Despite the high output of the SR drive, the motor was only 75% of the overall weight of the induction motor. The torque/speed curve shown in Fig 29(b) illustrates the high peak-to-continuous output of the drive and the excellent low-speed torque capability. The overall efficiency of the drive system, including the electronics, is between 73-77% over the operating speed range of 1500-15,000 rev/min.

A further comparison has been made with a somewhat larger machine. An SR drive has been built using a standard induction motor TEFC D80 cast aluminium frame. Whilst using more active material, the length between winding overhangs for the SR motor and the induction motor were identical, with identical airgaps also being used. For this comparison the induction motor was supplied from a state-of-the-art variable-frequency inverter. At 1400 rev/min, continuous output (just within a Class B rise), the induction motor could achieve an output of 748W (5.1Nm) with a total system efficiency of 74.8%. The SR drive could run continuously at 1500 rev/min with an output of 1.13kW (7.2Nm) at an overall efficiency of 81.6%. There is clearly a significant increase in output for the SR drive system, which is even more impressive when the comparison is carried out at lower speeds.

5.2.3 Medium and high power drives

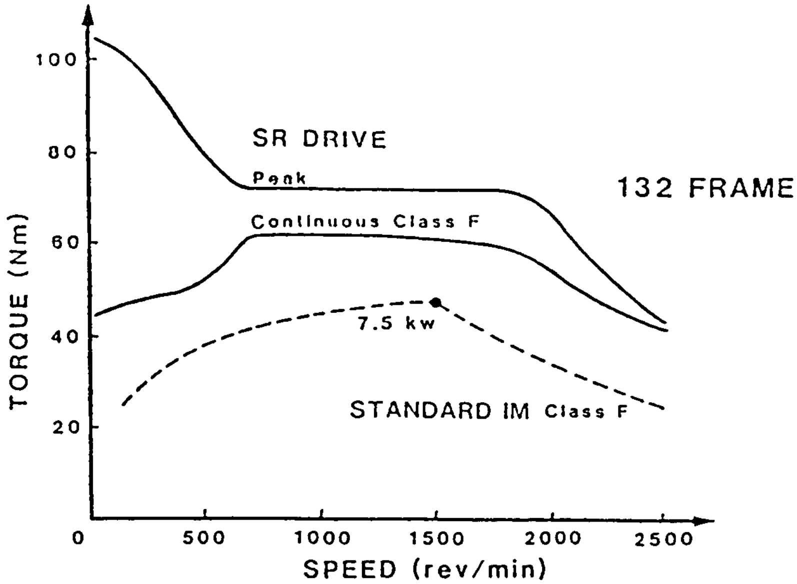
This category covers drive systems from a few kilowatts up to several hundred kilowatts, which are usually supplied from 380-460V, three-phase mains. A new generation of SR drive designs has now been tested, ranging from 4kW to 110kW and these drives are now showing significant improvements over first generation designs and have excellent performance characteristics compared to conventional inverter-fed induction motors.

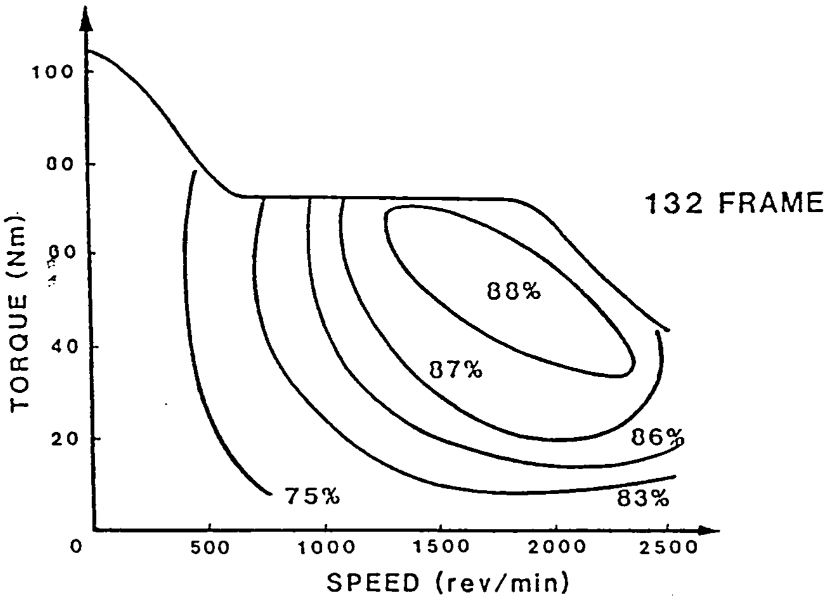
These larger industrial drive systems use conventional TEFC frames for the SR motors with IGBT-based power converters employing ASIC and microprocessor technology. (See Allenwest Motion Master for more details [36]).

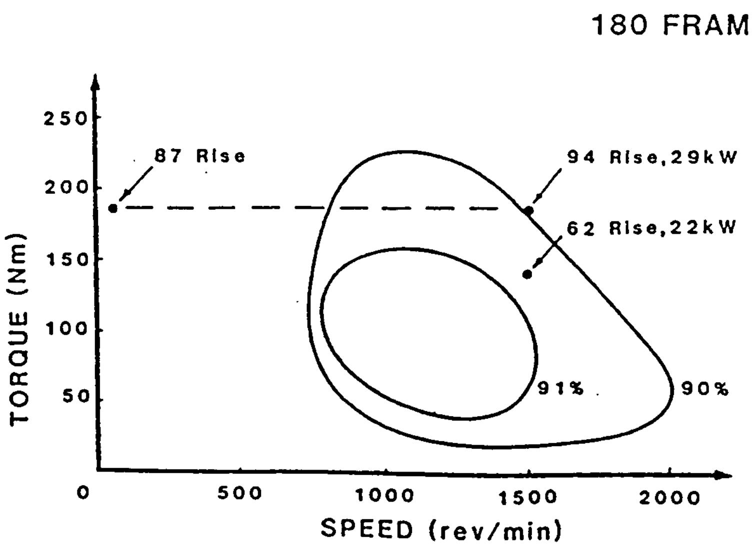


S.R.DRIVE PROVIDES
2 TIMES INDUCTION MOTOR OUTPUT
S.R.MOTOR DRIVE
OUTPUT (Class B)
1400 rev/min -- 170 W
2800 rev/min -- 352 W
10000 rev/min -- 700 W
Weight -- 3.54 kg
3-PHASE INDUCTION MOTOR
OUTPUT (Class B)
1400 rev/min -- 90 W (4-pole)
2800 rev/min -- 180 W (2-pole)
(50Hz sinusoidal supply)
Weight -- 4.4 kg
NOTE: BOTH MOTORS HAVE IDENTICAL Stator Stack O.D. Airgap
Grade of Steel Cooling
(a)
Torque (Nm)
3
2
0
measurement limit
peak o/p
IM pull out torque
continuous o/p.
class B
2-pole IM
4-pole IM
5000
10000
15000
Speed (rev/min)
(b)

Figure 29







Figures 30, 31 and 32

A typical performance characteristic for a 132 frame new-generation drive system is shown in Figure 30. It can be seen that the continuous output torque/speed characteristic is about significantly higher than that of a standard inverter-fed induction motor in the same frame size and with the same temperature rise. The SR drive performs particularly well at high torques and low speeds, for example, the 132 drive operating at 10% of base speed and rated output gives a two times advantage over published figures for an inverter-fed induction motor of the same frame size.

The overall system efficiency map for the same drive is given in Figure 31, which shows a very high efficiency over a wide torque/speed range. These figures are achieved with motors built using identical lamination steel and airgaps to standard induction motors.

Another example of good thermal performance is shown in Fig 32, which shows the output of a 180 frame drive. This drive achieves 29kW at 1500 rev/min compared to less than 20kW as an inverter-fed IM and it also gives a particularly low temperature rise at 50 rev/min and rated torque.

This new generation of industrial SR drives have the option of full 4-quadrant control and the very high torque-to-inertia ratio and control bandwidth of the SR system provides excellent dynamic response even without the use of an external tacho feedback. However, as with all drives, the eventual level of dynamic performance is dedicated mainly by the quality of the speed feedback signals. Hence the addition of a high quality tacho or resolver would allow wider controlled speed ranges and higher bandwidths.

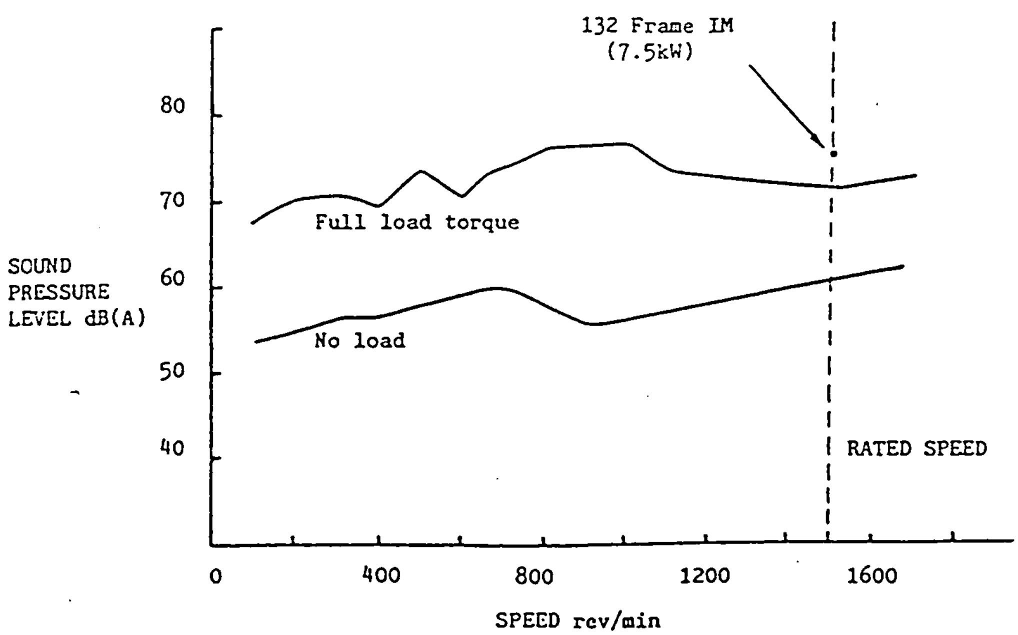


Figure 33

Acoustic noise has in the past been put forward as a problem with general-purpose SR drives. However developments in electromagnetic design and electronic control strategies have greatly improved acoustic noise levels such that equivalence or improvement over inverter-fed IMs is now possible. Figure 33 illustrates a carefully controlled acoustic noise

measurement for a 132 size 10kW SR drive under no load and rated torque conditions for a range of speeds. It can be seen that the full-load noise level is about 72dB(A) which is only marginally greater than an equivalent induction motor running from a sinusoidal voltage source.

Torque ripple has also been reported as a major problem for SR drives. Although experience at SR Drives Ltd., involving a very wide range of applications has not shown any problems.

5.2.4 High performance industrial drives

This type of application is normally supplied by conventional dc drives or brushless PM drives or more recently flux vector controlled induction motors. Power levels can be as high as 100kW, but the drives must still provide rapid and smooth control of load torque. Again the SR drive is particularly well suited to this application because of its dynamic performance, high specific torque and excellent cooling. The robust nature of the motor is also increasingly important at larger sizes where secure constructional techniques for conventional machines become difficult and expensive. The following data describes a recent example of this type of high-performance SR drive system:-

- 112 Through-ventilated frame.
- Continuous rating 12kW.
- Peak output 18kW.
- Constant torque to base speed 1800 rev/min.
- Constant power from base speed to 4000 rev/min.
- Full 4-quadrant operation.
- IGBT-based controller.

These characteristics are typical of a high performance dc system. A photograph of the drive system is shown in Figure 34.

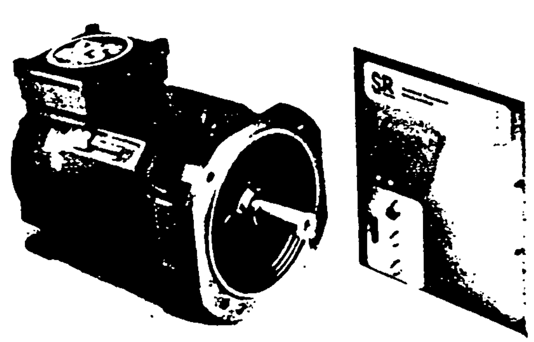
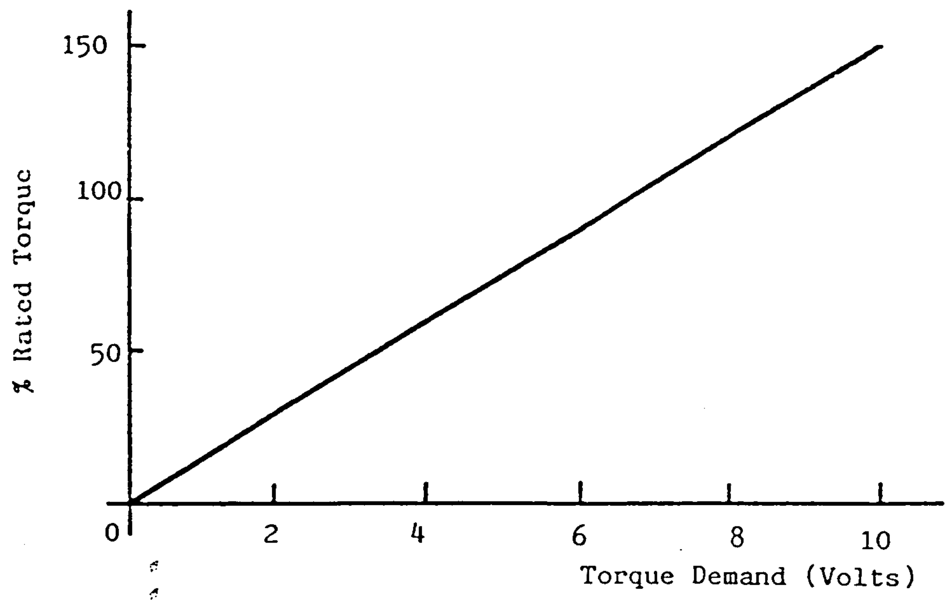
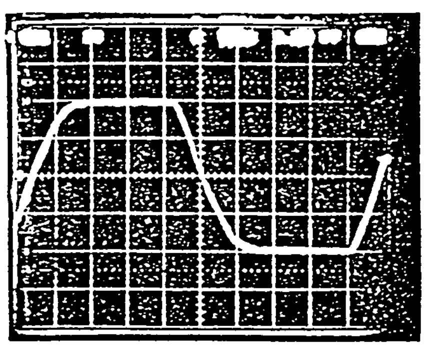


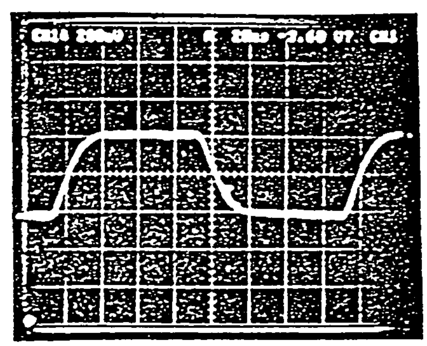
Figure 34





Step reversal +2000 to -2000 rev/min

Timebase 50mS/div



Square wave response 1500 - 1750 rev/min

Timebase 20mS/div

Figures 35 and 36

The SR system provides excellent control with rapid response rates. Figure 35 illustrates the linearity of torque demand against torque output up to base speed. Figure 36 shows two examples of dynamic response with the drive running unloaded.

The peak torque/inertia ratio is 6000 rads/sec^2 and the closed-loop speed control bandwidth is approximately 100Hz.

SR drives of this type can provide wide constant power operating regions without major penalties on motor specific output or power converter ratings, making this form of drive an excellent choice for machine tool and similar applications.

The use of conventional dc machines for high performance drives is now in decline and the flux vector controlled induction motor is emerging as a good brushless alternative to the dc drive. The SR drive system can also offer a brushless drive, with performance that matches or exceeds the best flux vector controlled induction motor and is finding increasing application in the dc replacement area.

5.2.5 Product Range Example

A range of high-performance SR drive systems has recently been launched by Sicme Motori in Italy aimed at the conventional dc general-purpose drive market area. The product range, called Relu-speed, covers power levels from 8kW to 120kW in seven motor frame sizes and a variety of cooling and enclosure options.

Figure 37 illustrates the drive performance and shows an example from the motor range.

The drives provide full 4-quadrant operation with IGBT-based power switching and microprocessor-based controls, including a full range of programmable interface options.

The present range will be extended to provide higher power levels in due course.

AZIONAMENTI RELU-SPEED CON MOTORI XMP. PRESTAZIONI E DATI TECNICI

GRAND. MOTORE XMP	POTENZA kW	VELOCITÀ BASE min^{-1}	VELOCITÀ MAX min^{-1}	CORRENTE nominale A (*)	CORRENTE di picco A(**)
80	8	4000	6000	17,5	27
90	10	3500	6000	23	35
100	15	3500	6000	31,5	47,5
112	22	3500	5500	50	75
132	35	3000	4500	80	120
160	75	3000	4500	165	250
180	120	3000	4500	255	385

(*) Corrente assorbita da linea trifase 380 V 50 Hz con carico nominale a velocità base (valori indicativi)

(**) Valore di picco della corrente nominale assorbita dal motore

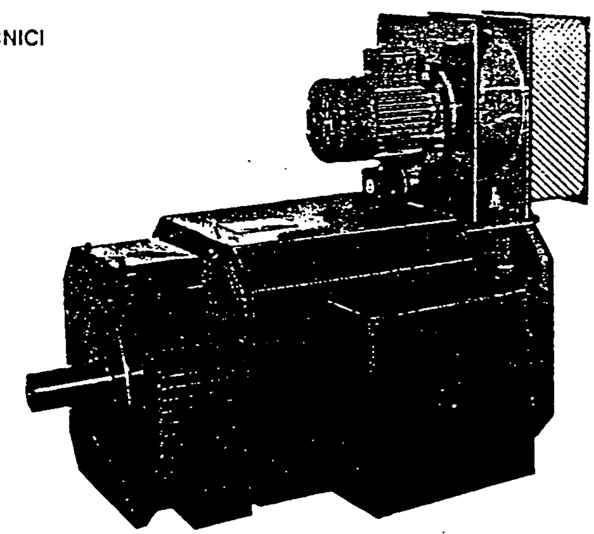


Figure 37 (Courtesy of Sicme Motori.)

5.3 Household appliances

Small drive systems for domestic or household appliances are becoming an important application area for SR drive technology. The main developments in this area are aimed at replacing the triac-controlled universal motors commonly used for a variety of variable-speed domestic applications. Developments are currently in progress in the following areas:-

(1) Automatic washing machines (front loading).
(2) Automatic washing machines (agitator style).
(3) Food processors.
(4) Vacuum cleaners.
(5) Garden equipment.

Figure 38 shows the torque/speed characteristic of a small SR motor compared to a universal motor with the same core dimensions. The SR motor provides 2-3 times the torque output when operating to the same thermal limits over the same speed range (0-15,000 rev/min).

In general the SR motor provides a substantial saving in active material compared to the universal motor which is a particularly important factor in this high-volume, low-cost market area. Figure 39 shows an example of an SR motor and universal motor designed for the same duty to illustrate the size advantage.

The motor material saving helps pay for the more complex electronics required by the SR drive. In order for the SR drive to be competitive, the electronics must be manufactured at low cost, which requires a very high level of integration including a fully custom power switching module and custom control circuit.

The simple requirements of the SR control coupled with the low price for Mosfet switches and custom logic chips, have made the SR system fully competitive with existing drives. The household appliance application can be expected to be a rapidly expanding area for SR technology.

Although drive cost is the dominant factor for domestic appliances, other performance features are becoming more important, particularly acoustic noise levels. Recent work carried out by SRD Ltd has produced SR drive systems with substantial noise reductions compared to existing conventional technology. The following figures show noise measurements for a front-loading automatic washing machine operated by an SR drive.

Condition (Motor Speed)	**Noise Level (dBa)**	
Wash (530 rev/min)	42	
Spin 1 (4500 rev/min)	51	Sound pressure level
Spin 2 (6500 rev/min)	58	measured at 1 metre
Spin 3 (8500 rev/min)	58	in a semi-anechoic
Spin 4 (12000 rev/min)	62	chamber.

10:1 belt ratio, 5kg drum load.

Note these figures show a substantial improvement over conventional universal motor drives and also inverter-fed induction motor drives and should eliminate the erroneous perception of high noise levels from SR drive systems.

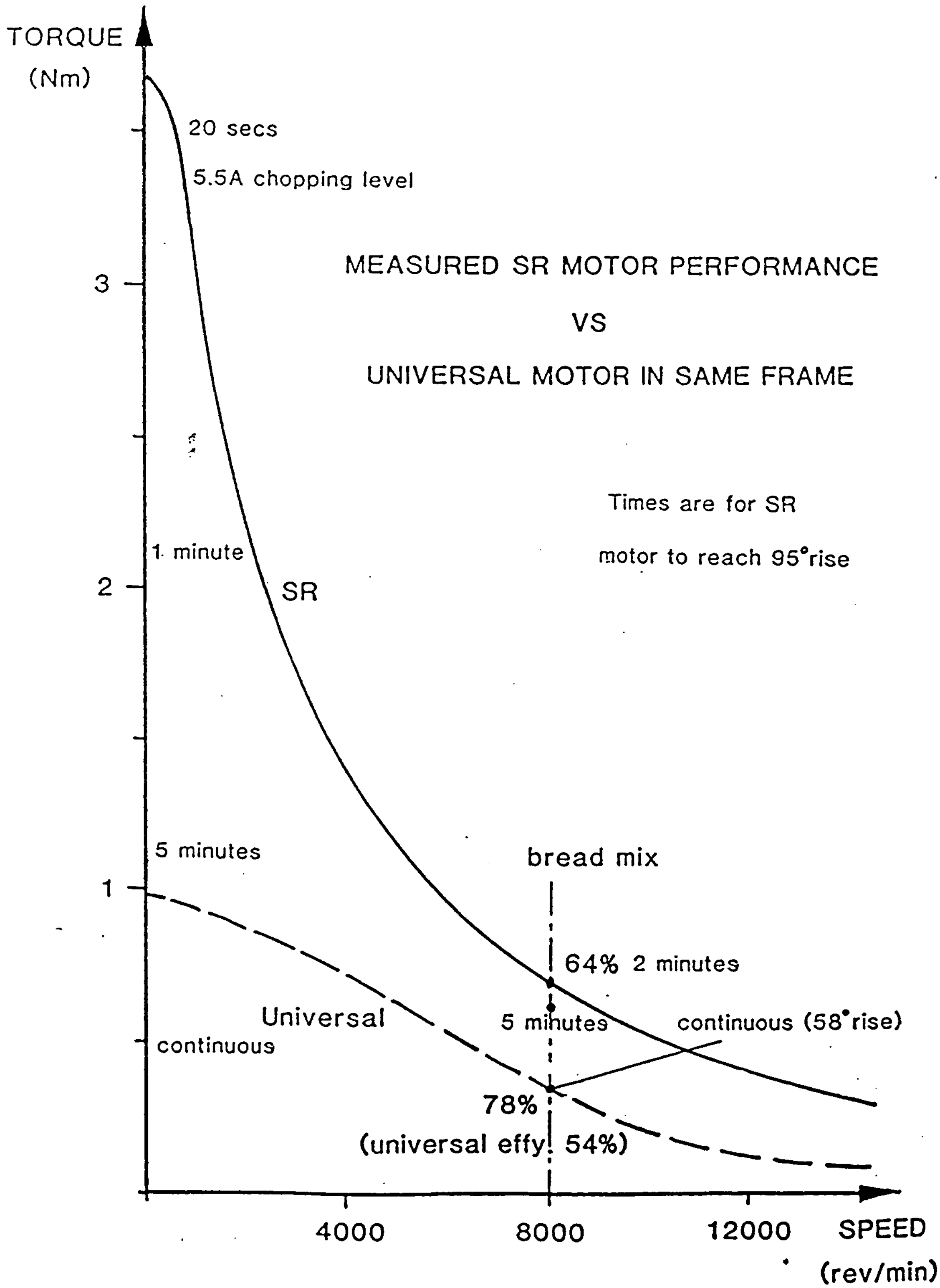


Figure 38

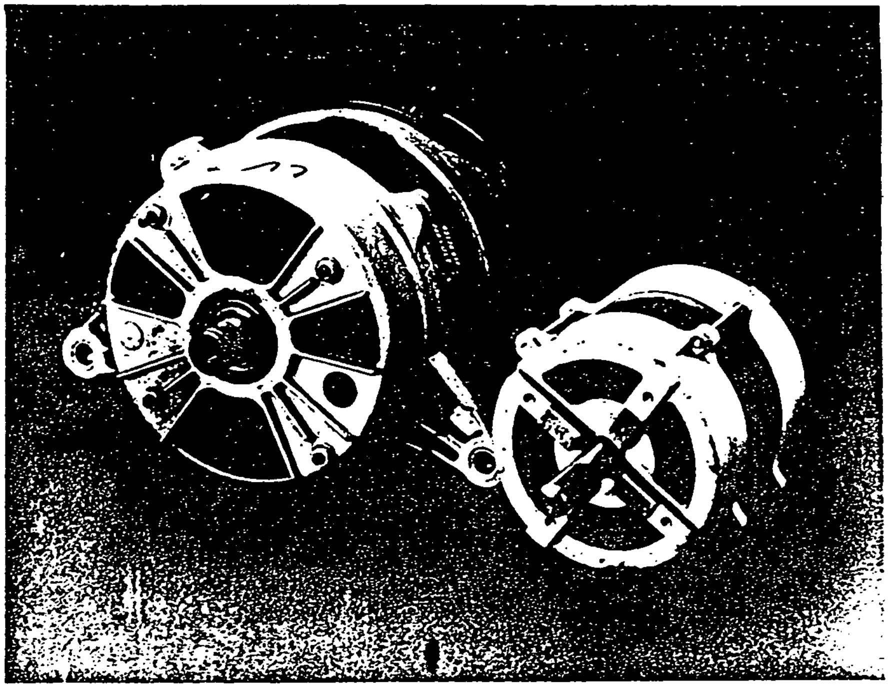


Figure 39

5.4 Electric Traction Applications

5.4.1 Introduction

SR drive systems are particularly well suited to electric traction applications, in fact much of the early SR development work was directed towards battery-electric vehicle drives. Apart from traditional traction applications, such as rail vehicles and forklift trucks, there is now renewed interest in battery-powered road-going vehicles driven by environmental issues. The SR drive system is uniquely well suited to meet these market areas and the following list highlights some of the important features that make SR drives particularly attractive.

- Torque/speed characteristics

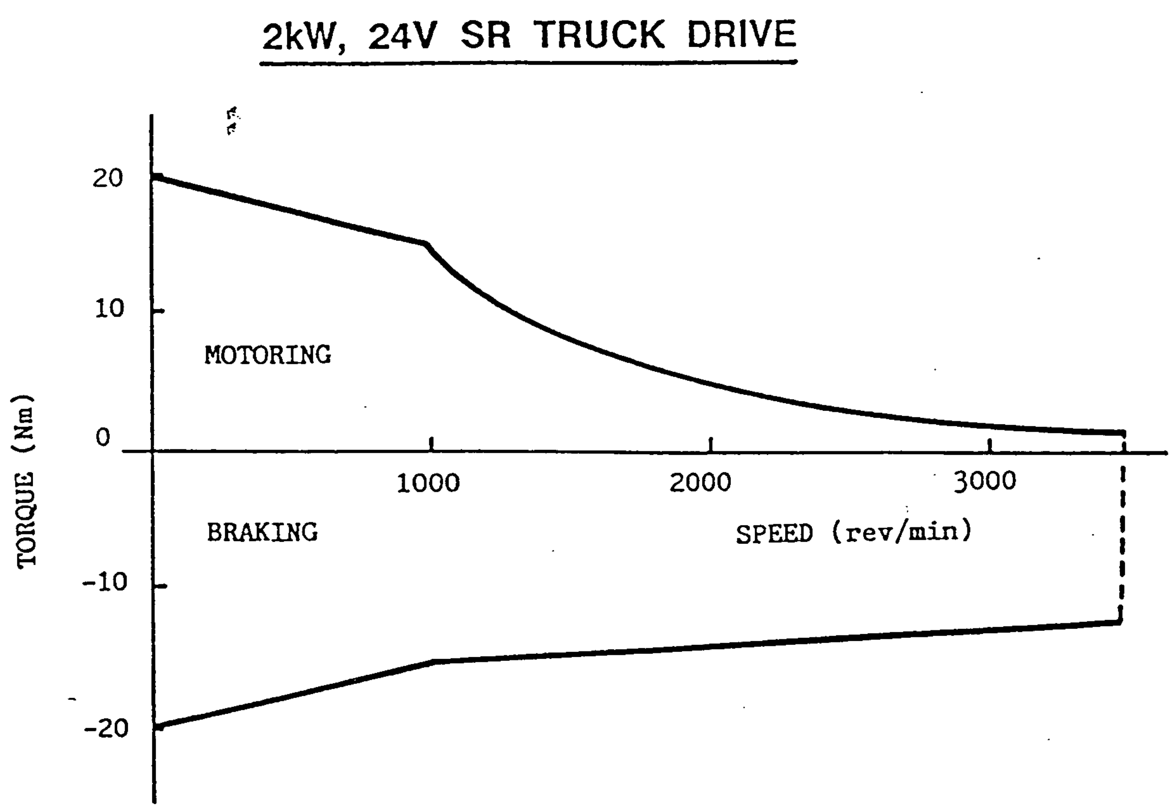
Most traction systems require a high starting torque with a constant torque up to a base speed followed by a wide constant power range. The peak torque envelope is usually substantially greater than the equivalent continuous condition, which is ideally suited to an SR drive.

- Efficiency

The SR drive provides an excellent overall efficiency over a wide torque/speed range which is a particularly important feature for battery-powered equipment where energy efficiency is vital to maintain vehicle range.

- Robustness and reliability

The simple mechanical construction of the SR motor provides an extremely robust system with none of the familiar problems of brushed machines and wound rotors. The electronic controls are also very reliable and fault tolerant. Both of these factors are necessary for electric traction.



2kW, 24V Pallet Truck SR Drive

Modified Torque Speed Characteristic
to include High Speeds and Emergency Braking

Figure 40

● Controllability

The SR drive system provides the controllability of a dc machine with full control of both armature and field which is ideal for traction. The SR drive also does not exhibit inherent instabilities which can occur on inverter-fed induction machines. The control characteristics are also very flexible and can be programmed to suit a particular application.

● Size and weight

The high specific output of the SR motor coupled with its ability to operate at very high speeds gives a very compact and light drive system.

● Cost

The volume manufacture cost of the SR drive is lower than other forms of brushless drive.

The following illustrates three examples of SR drives applied to traction application.

5.4.2 Battery powered pallet truck

This application uses the SR drive for the main traction drive to drive a 2.5 tonne (gross weight) vehicle pallet truck. The drive requires a high torque at low speeds with fine controllability to allow 'inching' of the load in confined spaces. The drive operates from a 24V lead acid battery.

The torque/speed characteristics for the drive in the motoring and braking quadrants is shown in Figure 40. Note the very high braking torque required for emergency electrical braking (up to 5 x rated motoring torque).

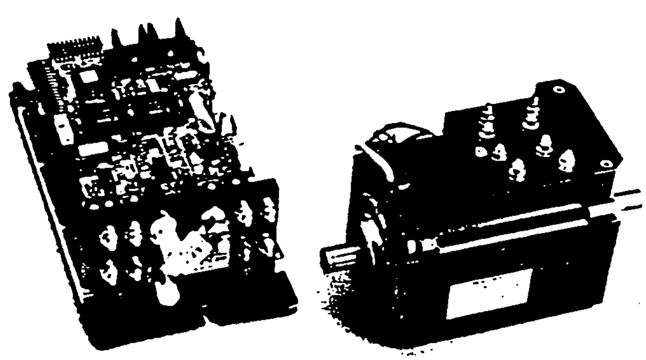


Figure 41

The motor and controller in prototype form is shown in Figure 41. Note that the motor is only slightly larger than half the volume of the conventional dc series motor which it replaces and the Mosfet-based controller is roughly the same size as the dc chopper. The cost of the drive system is competitive with the conventional dc system, whilst offering a number of beneficial features.

5.4.3 Battery electric delivery vans

These examples are taken from some early development work carried out at Leeds and Nottingham Universities which resulted in what was probably the first SR powered road-going vehicle. SR drives were built for two vehicle sizes:-

- 20kW (small van).
- 50kW (large van).

Both drives operated from a 180V lead acid battery. The base speed of the drives was low (750 rev/min) with a 3:1 constant power range. These drives were technically very successful giving a high efficiency and good specific output.

The small van shown in Figure 42 was successfully demonstrated in 1982.

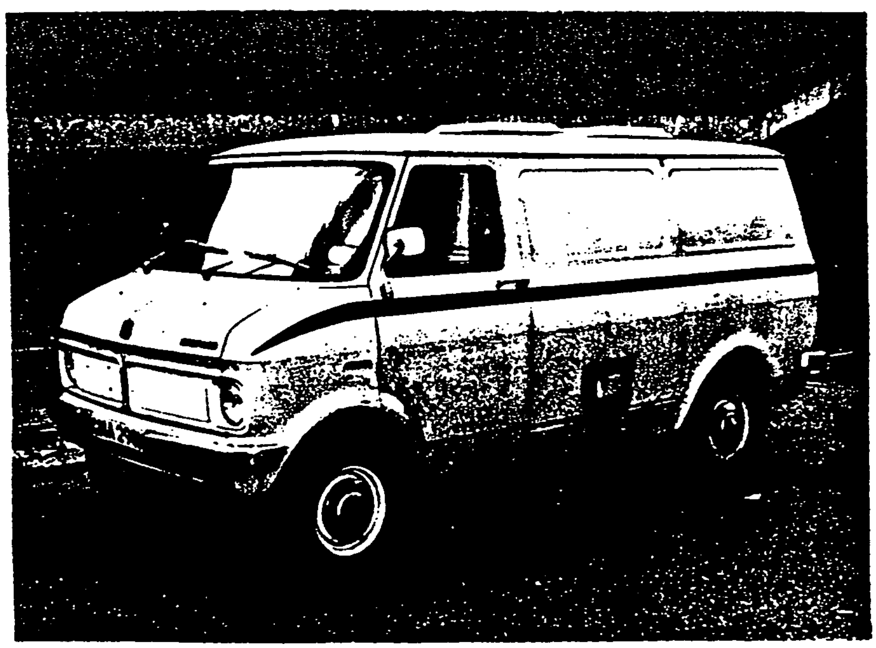


Figure 42

5.4.4 Light rail traction

Figure 43 shows a streetcar (tram) operated by GEC Traction on the Blackpool tramway in 1985. The tramcar was converted to SR traction drives by SRD Ltd. This was achieved by modifying four standard industrial drives to give a total peak power of 120kW.

The modification essentially involved software changes to alter the shape of the torque/speed characteristic. The tram performed well and was operated for 15,000 miles of revenue earning service and proved to be both quiet in operation and very manoeuvrable.

Figure 43

5.5 Automotive Applications

Apart from main traction drives, SR technology is finding many other applications in the automotive industry. The use of electric motor drives for auxiliary functions in cars is increasing rapidly and the SR drive can provide an attractive solution for many applications. The main reason for interest in SR technology is low cost and robustness required to operate in the very harsh automotive environment. Programmable control is also important since many drive systems will be required to interface with vehicle management systems. Some applications are listed below:-

- SR generators (alternator replacement).
- Pump drives.
- Fan and blower drives.
- Servo actuators.
- Windscreen wipers.

As an example, the SR generator is particularly interesting. In this case the SR machine is operating as a generator to maintain the automotive bus at a required voltage. The SR machine is able to provide efficiency and size advantage over conventional alternators whilst also providing some beneficial control features.

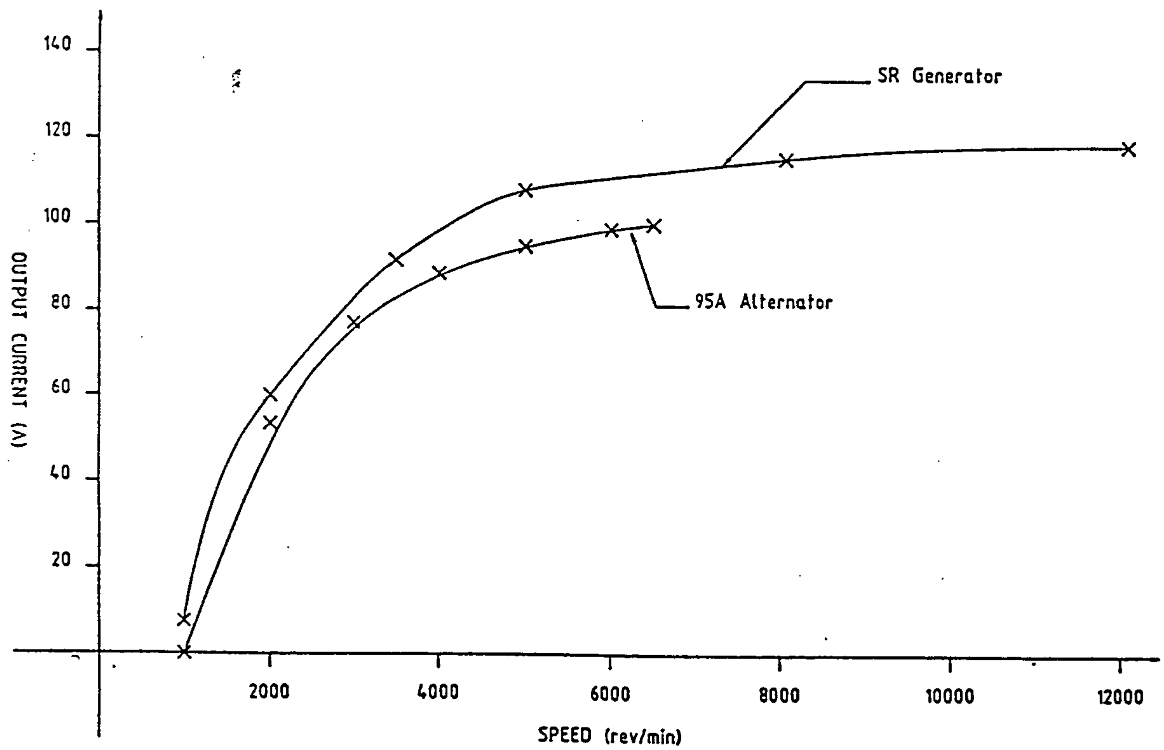


Figure 44

Figure 44 shows the output curves for a 95A SR generator designed for automotive applications.

5.6 Mining Equipment

Variable-speed drive system designs for use underground are dominated by space constraints, extreme ruggedness and the need for very high efficiencies. SR drives have been designed for this very harsh environment and the example shown below is a coal shearer machine haulage drive, which is essentially the traction drive which propels the main cuttingequipment into the coal face. The system is manufactured by BJD Ltd, UK.

The motor is rated at 35kW with a base speed of 750 rev/min and it is cooled by a water jacket. This form of cooling is very effective since most of the heat to be dissipated is generated in the stator.

The electronics operate directly from the 1100V supply and use GTOs as the main switching devices. The power switching elements are also water cooled and built into a flameproof enclosure.

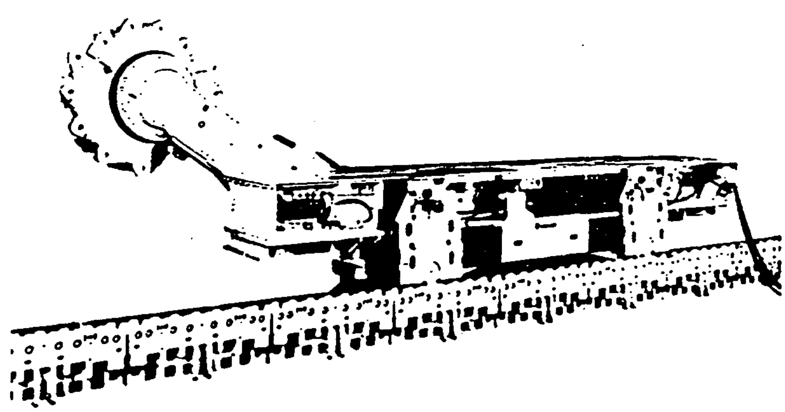


Figure 45

Figure 45 illustrates two SR motors driving a coal shearer machine (courtesy BJD Ltd).

High power SR drives for other general-purpose applications are now under development. These drives will be rated at 150kW and 300kW and are intended to replace induction motors in a variety of underground applications.

5.7 Aerospace applications

SR drive systems have been found to be ideally suited for a number of applications in the aviation industry. The main reasons for the suitability of SR technology in this area are its light weight and small size coupled to high efficiency and high speed capability. However, one of the most critical features for aviation applications is high reliability. It is now generally recognised that SR technology can provide a very high degree of fault tolerance. Designs have been carried out for jet engine starter/generator units, oil pumps and a variety of fuel pumping applications. Much of this work has been carried out by GE (USA) and is detailed in references 56,57,58.As an example, the starter generator unit produces an output of 50kW at 50,000 rev/min and has a stack OD of 6.25 inches and a length of 3.3 inches. As a generator, this unit provides efficiencies of up to 93%.

5.8 Servo systems and actuators

SR drive systems are particularly well suited to servo and actuator applications because of their high dynamic response. The torque/inertia ratio and the control bandwidth are both very high and these two fundamental parameters provide the necessary 'building blocks' on which to form a full servo system. There are now many examples of SR servo systems and some will be shown here to illustrate opposite ends of the spectrum.

(a) Sliding door operator system

The first example is a direct-drive positioning actuator, developed by S R Drives Ltd. for Besam of Sweden, to operate automatic sliding doors in public buildings. The complete drive is shown in Figure 46. It replaces a conventional dc motor, gearbox and door control system and is housed in the frame above the doors.

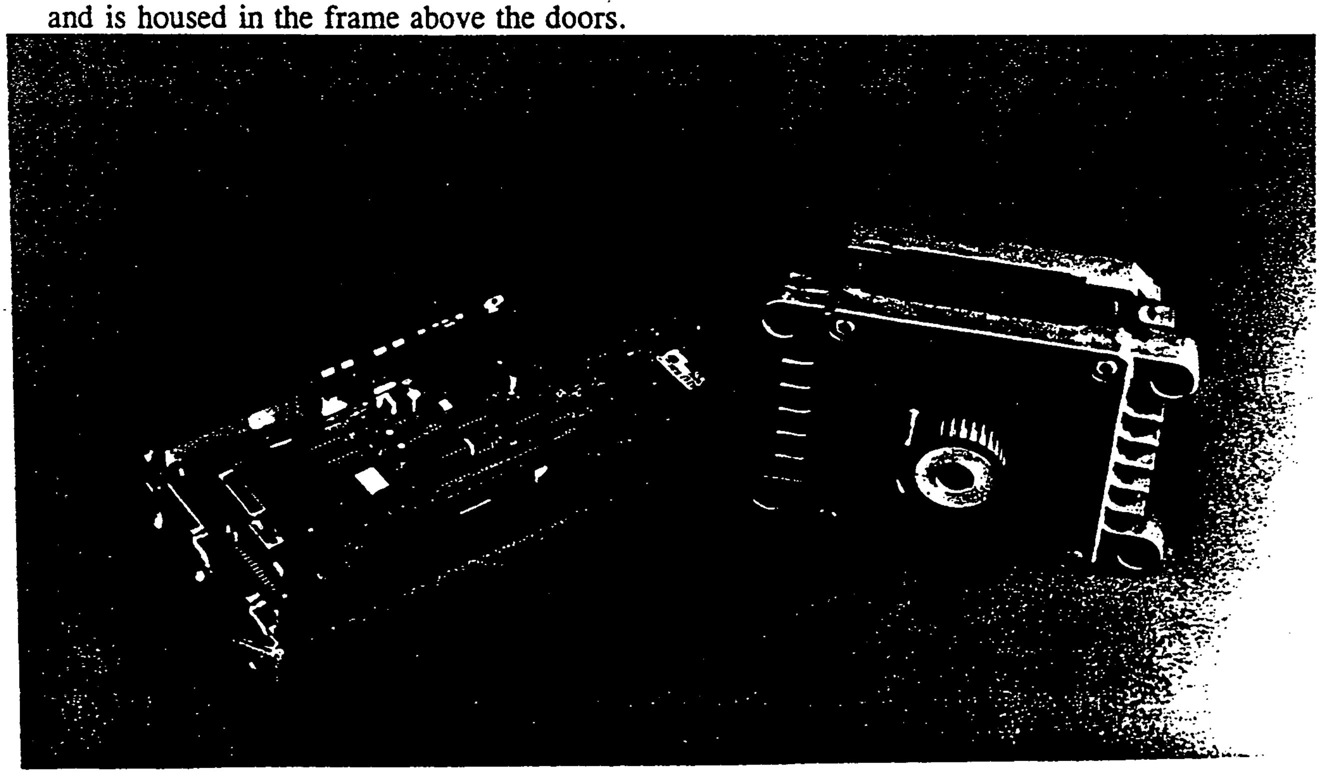


Figure 46

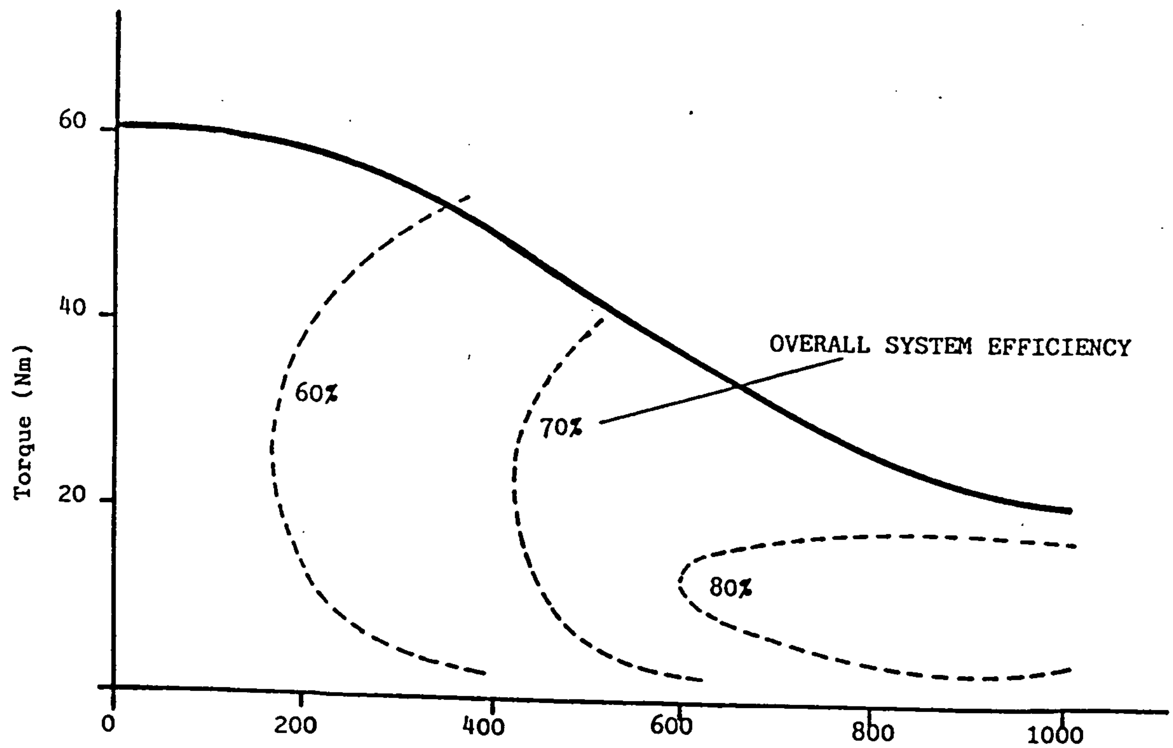
Both cost and space constraints are extremely severe in this application, but the SR system is cost effective and the control system, incorporating both ASIC and microprocessor technologies, includes all the necessary safety requirements for the doors. A wide range of door sizes (and hence inertias) can be controlled without hardware changes to the controller. The motor includes a simple encoder which is used by the control system to track the door movement; this saves the cost of a separate encoder previously required.

The drive produces a peak shaft torque of 5 Nm, has a maximum speed of 350 rev/min and operates the doors in a cycle time, typically, 8s. On power-up, the system'measures' the door travel and uses this information to optimally control the operation of the door. Both the motor and the control board are made in the UK, and the drives are being sold world-wide.

(b) Direct drive high torque actuator

This is an application-specific SR drive design for a high-volume, low-cost actuator requirement. The high load inertia necessitates a high drive torque to achieve the required acceleration and deceleration times without the use of a gearbox. The SR drive must provide all of the necessary control whilst coupled directly to the load and thus replaces a conventional high-speed motor and 20:1 step-down gearbox.

Note: the load inertia is approximately $0.35 Kgm^2$ and the SR motor rotor inertia is $9.65 \times 10\text{-}3 Kgm^2$.



Direct Drive Actuator SR Motor. Torque-Speed Characteristic

Figure 47

The torque speed characteristic of the drive is shown in Figure 47 illustrating the high-torque, low-speed nature of the application. Only the forward motoring quadrant is shown, but the drive system is fully four-quadrant and the other three quadrants are symmetrical.

The SR motor implementation uses a frameless construction with a square lamination (185mm square). The motor is totally enclosed with an overall length of 127mm. The positioning coder system uses opto-electronics and is housed inside in the motor enclosure behind the non-drive end bracket.

Figure 48 shows a photograph of a prototype motor undergoing tests.

The electronic controls uses IGBT switching technology and operate directly from a single phase 240V mains supply. The control system is all-digital and provides some adaptive speed trajectory selection to obtain the optimum transition on change of position.

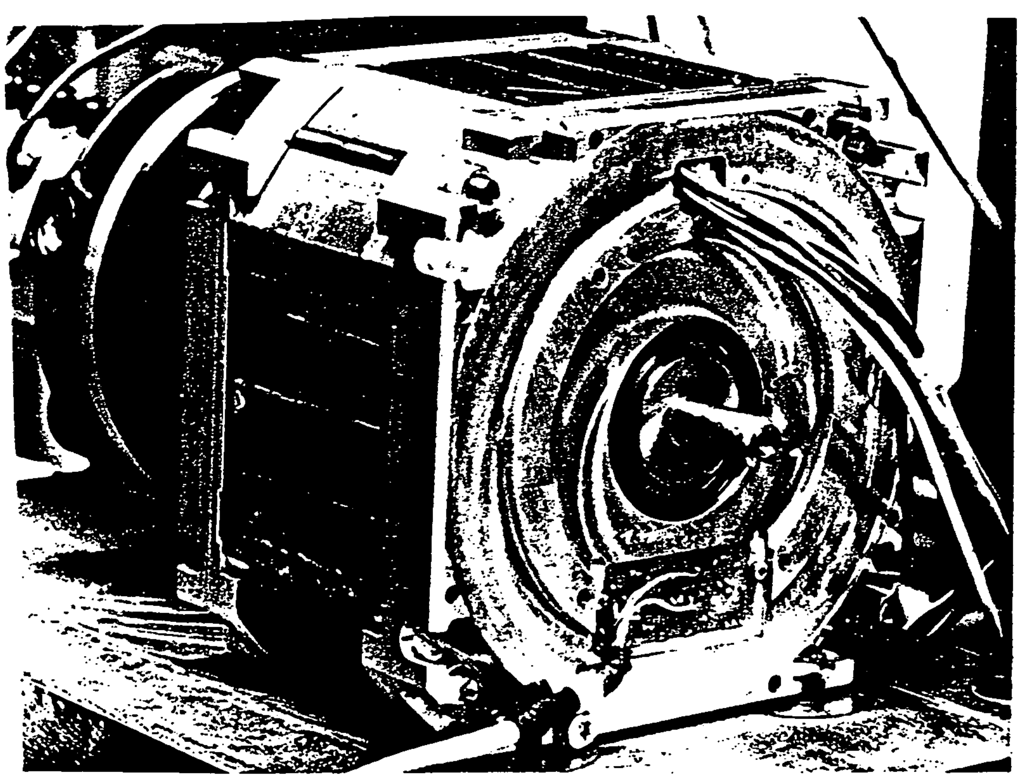


Figure 48

(c) Very high power servo drive

There is an increasing requirement for very high power drive systems with servo-level dynamic performance. A system recently designed and commissioned by SR Drives Ltd. has the following parameters:

- 225 force-ventilated frame
- Inertia approximately 1.5kgm^2
- Peak torque 5200Nm at 500rev/min (=270kW)
- Continuous output 135kW
- Symmetrical operation in 4 quadrants
- IGBT-based controller operating from 3-phase, 380V supply.

The combination of low inertia (approximately half that of an equivalent dc machine) and high specific torque (40Nm/litre active volume) gives outstanding performance. For example, the drive will accelerate from rest and settle at 500rev/min in 20msec and can reverse to settle at -500rev/min in 40msec. This level of performance far exceeds the best dc servos available at this power level.

(d) Small high speed position servo

This example illustrates a small high speed servo system, developed by Hewlett Packard, which is used in a range of plotters and computer peripherals as an acoustic position servo [15]. The motor is shown in Figure 49 and it provides a torque/inertia ratio of above 100,000 rads/sec^2 and provides acceleration about 70% greater than the equivalent output dc motor.

This positioning application shows that torque ripple and linearity have not been found to cause problems when implementing SR servo systems.

5.9 Other applications

SRD Ltd is involved in many other developments for application-specific designs too numerous to detail in these notes. These applications include:-

- Fan drives.
- Pump drives.
- Compressor drives.
- Textile equipment.
- Metal processing equipment.

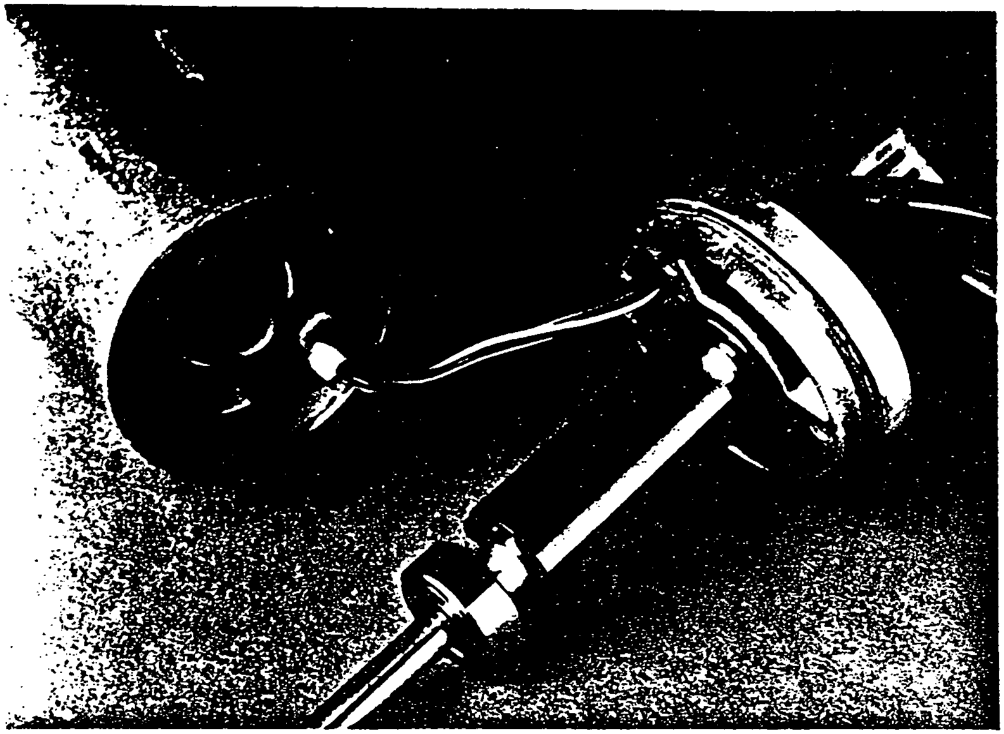


Figure 49

It is becoming apparent that almost any application requiring a motor drive system can benefit/utilise an SR drive system.

5.10 Cost and manufacturing implications

The question of cost is always fundamental to practical take up and in the case of new, or relatively new, technology such as SR it is particularly crucial. In general, it is safe to state that costs for SR drives compare at least favourably and frequently very advantageously with existing conventional drives (even when setting aside their performance advantages). Two different aspects and approaches to illuminate this matter are addressed below.
Firstly, so far as "medium volume" products are concerned there is, as compared with say inverter-fed induction motors, an almost one-to-one situation so far as materials, components and production processes and tolerances are concerned. So far as the electronics is concerned, power switches are rather less stressed in the SR system than in the inverter, and the control complexity is similar to, or simple than, standard PWM inverter strategy (and significantly simpler than vector control strategy and implementation). Accordingly, electronics costs are lower per "unit" performance than they are for the induction motor. ASIC techniques are now standard and, depending upon application, eg high starting torques, costs may beconsiderably lower.

So far as the motor is concerned, manufacturing cost estimates vary from one company to another, but generally they are favourable to the SR machine and are certainly so when it comes to smaller or to high performance drives. Automatic production line costs are put at less than one half of those for universal machines.

Secondly, taking the case of high volume products, as for domestic appliances, the automobile industry or large specialist OEM markets, the key is in the successful integration of the electronics. The SR motor is very much smaller and cheaper than the conventional one it replaces, perhaps one half of the active volume and one half of the cost, but substantial electronics has to be introduced instead of the conventionally very simple, low cost items. Suffice it to say that this has received, and continues to receive, considerable attention and very impressive fully integrated drives - both power and control sections - are now becoming available in production quantities.

5.11 Conclusions and Future Potential

It will be evident from the examples described above that SR technology is now being applied to a wide range of products. This range covers a full spectrum of power, torque and speed levels and also system complexities, ranging from very simple domestic appliance systems to very complex industrial process control equipment. Indeed, there are many other applications under development, not included here, which will become public in the near future.

As with all new technology, the initial market penetration has been slow, but it is now accelerating rapidly. Some market areas traditionally have very long cycle times, which limit the speed at which new products can be introduced; this is typical of the domestic appliance and automotive areas. Other market areas tend to be very conservative and only introduce new technology when commercial pressures to do so become serious.

Two problem areas which have been put forward by many people for slow take-up of SR technology, namely acoustic noise and torque ripple, have now clearly been solved, although in reality they were not serious problems for most applications. There have already been introductions to the market in the industrial drive area and in OEM applications, including some very recently. Over the next two or three years an increasing number of new products will be launched, particularly in the following areas:

- Washing machines and other household appliances;
- Compressor systems;
- Centrifuges;
- Battery electric vehicles;
- Textile machines;

- Fans and pumps;
- Servo systems;
- Various industrial systems.

Some of the longer-term applications will include various aerospace equipments (generators, pumps, actuators) and various automotive uses. Road-traffic-compatible electric vehicles is also a good area for this technology, but the success is likely to depend on advances in other areas, particularly in battery technology.

The continuing drop in the cost of electronics will provide additional cost advantages for SR technology, and since the motor element of the drive system is particularly cheap, any reduction in cost of electronic control will have a greater implication for SR technology than for conventional drive systems and will help to enhance the cost-effectiveness of the technology across all applications.

6 ACKNOWLEDGEMENTS

The Authors wish to thank their colleagues at SR Drives Limited for their collaboration.

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